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CONTENTS

ARTICLES

NOTE

COVER

San Joaquin Kit Foxes

California Fish and Game 83(1):1-20 1997

WHITE STURGEON SPAWNING MIGRATIONS AND LOCATION OF SPAWNING HABITAT IN THE SACRAMENTO RIVER, CALIFORNIA

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Sixty sturgeon (59 white, *Acipenser transmontanus*, and one green, *A. medirostris*) were tagged with radio transmitters in the lower Sacramento River in late winter 1990 and 1991 and their movements during spawning migrations were followed. In spring 1991 and 1992, artificial substrate samplers were deployed in various habitats in areas of the Sacramento River used by spawning sturgeon. Upstream movement of tagged sturgeon could be quite rapid, up to 25 km/d, and was often stimulated by small increases in river flow. Downstream movement of females, assumed to be post-spawning migrations, were also rapid, as fast as 91 km/d. Sturgeon eggs were taken at artificial substrate sites where depths ranged from 1.8 to 4.6 m and flow velocities exceeded 1.0 m/s. Most spawning occurred from Knights Landing to several kilometers upstream of Colusa.

INTRODUCTION

The white sturgeon, *Acipenser transmontanus*, population in California is mainly associated with the Sacramento River and its combined estuary with the San Joaquin River. This population was commercially overfished in the last two decades of the 19th Century, prompting closure of the fishery by the California Fish Commission in 1901. Following brief re-openings in 1910 and 1916, the fishery was legislatively closed from 1917 to 1954. In 1954, a sport fishery was re-opened with a 102-cm total length (TL) minimum size limit and a daily creel limit of one fish. Under these regulations, annual exploitation rates were 0.056-0.083 in the 1970s, but increased to 0.087-0.115 in the 1980s (Kohlhorst et al. 1991). This increase in fishing mortality reduced population egg production by 35%. In response, the California Department of Fish and Game (CDFG) instituted a "slot" size limit of 117-183 cm TL designed to reduce annual fishing mortality of sturgeon > 102 cm TL to about 0.05, with only a negligible decrease in biomass yield. This action was also intended to increase egg production by reducing the harvest of females before first spawning and by protecting large, highly fecund females (Botsford and Hobbs 1986).

With adoption of this strategy to partially manage sturgeon on an eggs-per-recruit basis, it is assumed that the hatching success and mortality rates of young sturgeon to recruitment will not decline from present levels. Recruitment is positively associated with freshwater flow through the estuary (Kohlhorst et al. 1991), but little is known about the specific migration stimuli and spawning habitat requirements of white

sturgeon in the Sacramento River. Specific spawning habitat criteria have been examined for white sturgeon in the Columbia River (Parsley and Beckman 1994); lake sturgeon, *A. fulvescens*, in the Lake Winnebago, Wisconsin system (Kempinger 1988); and shortnose sturgeon, *A. brevirostrum*, in the Connecticut River (Taubert 1980, Buckley and Kynard 1985). However, these studies have largely centered on populations spawning immediately below impassable barrier dams or in very restricted areas and may not be directly applicable to white sturgeon in the Sacramento River.

Identification and protection of spawning habitat is vital for the maintenance of the population and the sport fishery. Historical spawning habitat has been lost in California, mostly due to dam construction. The San Joaquin River may have supported a larger spawning population than at present before the upstream diversion of most of its flow for agricultural irrigation (Moyle 1976). In the Sacramento River, white sturgeon spawned upstream of Shasta Dam before it was constructed(1940-1945), as evidenced by the relic population above this impassable barrier (Fiske[1] 1963). However, Kohlhorst (1976) found no evidence of spawning upstream of Ord Ferry Bend (river kilometer [rkm] 297) in 1973. Hence, I report the results of a two-phased study using radio-telemetry to determine general spawning areas and artificial substrates to identify specific spawning habitats as evidenced by egg deposition.

STUDY AREA

The study area included the Sacramento River from Rio Vista (rkm 19) to Ord Ferry Bend (Fig. 1). At low flows (< 285 m^3/s) the river is tidal below Sacramento (rkm 95), with flow reversals upstream to Freeport (rkm 74); however, salinity seldom exceeds 1‰ at Rio Vista. From rkm 25 to Sacramento, the river is contained within rip-rap-armored levees. Depths at low water average about 6 m over sand substrates, ranging from 2 m in shoal areas to 15 m in the deepest holes. Widths range from about 125 m below major distributaries downstream of Walnut Grove (rkm 43) to about 300 m near Sacramento.

From Sacramento to Wilkins Slough (rkm 190) the river is low gradient (0.08 m/km), meandering, and confined within flood control levees. Between Sacramento and Verona (rkm 128) river width averages 150 m and depths range from 2 to 4 m during low flows. Rock wing dams, installed to maintain a navigation channel, are present in shoaling areas. Levees are generally rock armored and substrates are coarse and medium sands with some gravel in high velocity areas near wing dams. From Verona to Wilkins Slough the river narrows to about 75 m and is confined by armored and unarmored levees. Substrates are fine to medium sands and submerged snags are present. From Wilkins Slough to Colusa (rkm 231) the river gradient remains low, but substrates change to coarse sand and fine to medium gravels in areas with higher gradients. Snags are abundant in areas where flood control levees are set back from the river channel and the river is allowed to meander. Charted depths range from 0.3 m to 8.5 m at low flows.

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[1] Fisk, L.O. 1963. The Shasta Lake sturgeon fishery. California Department of Fish and Game, Inland Fisheries Administrative Report No. 63-12.

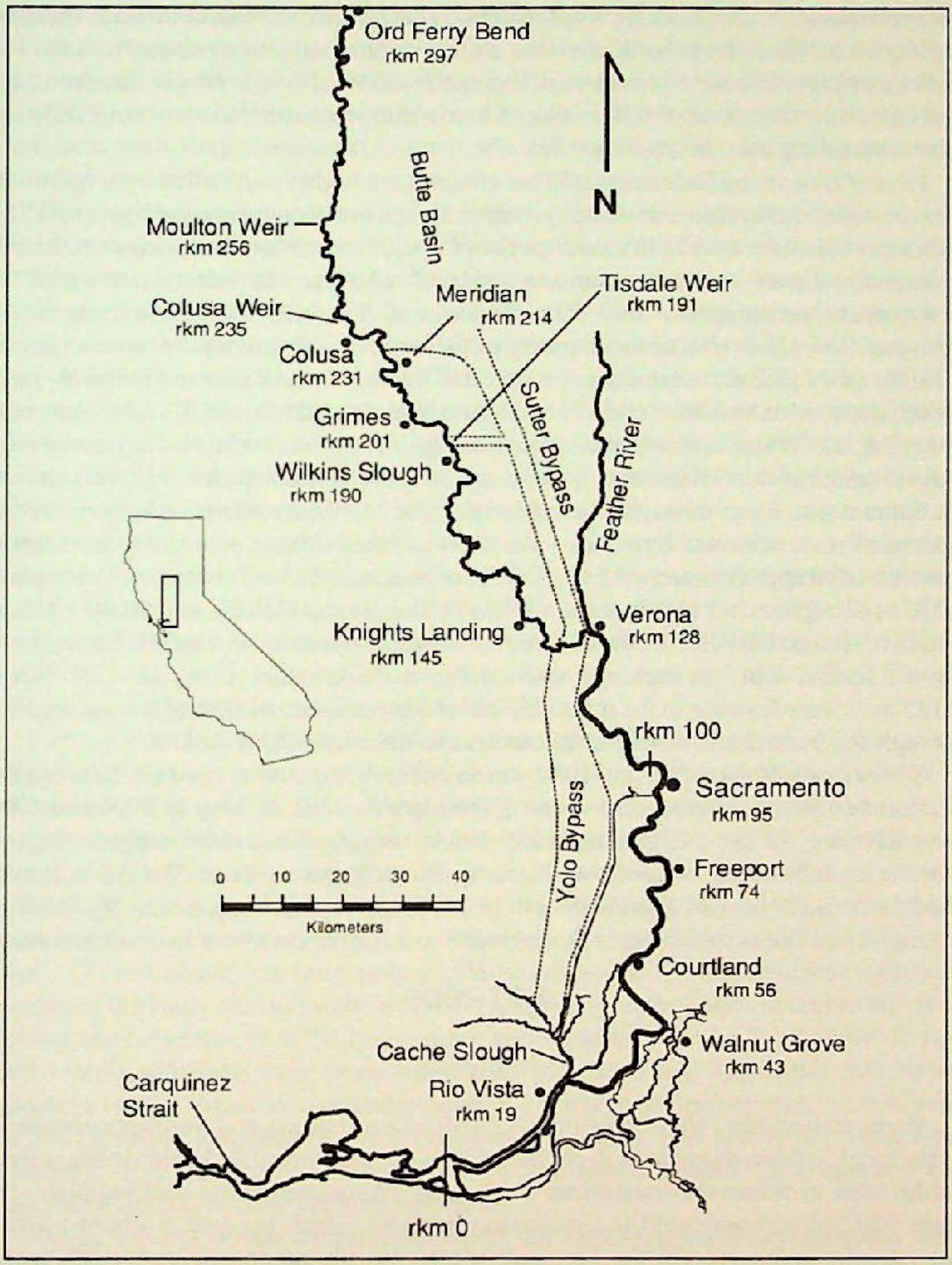

Figure 1. The white sturgeon radio-tagging and spawning habitat study area from Carquinez Strait to Ord Ferry Bend.

Between Colusa and Ord Ferry Bend (rkm 297) the river gradient averages 0.24 m/km and the river assumes a pool-riffle character. In this reach, flood control levees contain the river in a designated floodway 0.5-2.5 km wide and the river is free to meander

between the floodway levees, except in areas where armored banks protect levees and deciduous orchards from bank erosion. In this region, substrates range from mud in backwater areas to coarse gravel-small cobble in riffles. Most levees in direct contact with the river are armored with rock $\leq$ 0.5 m in diameter and this armoring includes a toe extending into the river bottom.

River flows in the Sacramento River channel are highly controlled by large water storage reservoirs and an extensive system of designated floodways and bypasses. The major storage reservoirs tend to reduce flows in the wet winter and spring months and to augment flows in the dry summer and fall when stored water is released for downstream consumptive use. The bypass and floodway system is designed to transport flows in excess of the capacity of the main channel. Major diversion points from the main channel, where water is diverted into the Butte Basin and Sutter Bypass, are located at Moulton Weir (rkm 256), Colusa Weir (rkm 235), and Tisdale Weir (rkm 191) (Fig. 1). Water in this bypass joins with the lower Feather River and crosses the main channel of the Sacramento River into the Yolo Bypass at rkm 132, re-entering the Sacramento River through Cache Slough (rkm 24). Since all major features of this system of reservoirs and bypasses have been in place (1968), maximum in-channel flow has been approximately 3,200 m^3/s at Sacramento, 835 m^3/s between Verona and Wilkins Slough, 1,240 m^3/s between Wilkins Slough and Colusa, and 10,400 m^3/s at Ord Ferry Bend (CDWR[2] 1974). The amount of water bypassed around the Sacramento River channel can substantially exceed the main channel flow; in 1986 when 3,185 m^3/s were flowing in the main channel at Sacramento, 14,000 m^3/s were flowing through the Yolo Bypass several kilometers to the west (CDWR[3] 1987).

Water years 1990, 1991, and 1992 were extremely dry. Average daily flows in the Sacramento River at Sacramento from 1 February through 31 May in 1990 and 1991 were 370 and 371 m^3/s, 43% of the 1955-1993 average. When radio-tagged sturgeon were being monitored, water flowed into the Sutter Bypass on only 2 d (15 m^3/s over Tisdale Weir, 27 and 28 March 1991). In 1992, the overall season was dry (46% of average), but flows increased at Sacramento to 1,350 m^3/s during February storms.

METHODS

Migration

Radio transmitters were based on a "C" cell lithium battery and were approximately cylindrical, 2.8-cm diameter x 8-cm long. Two plastic-coated, 1.5-mm stainless steel cables were cast into the transmitter 7 cm apart. A quarter-round backing plate, cut from PVC pipe, completed the mounting harness. Each tag had a 40-cm trailing antenna of stainless steel cable. Transmitter weight with antenna, mounting cables and

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[2] California Department of Water Resources (CDWR). 1974. Hydrological data: 1973. Bulletin 130-73, Volume II. Sacramento, California, USA.

[3] California Department of Water Resources (CDWR). 1987. Hydrological data for the Sacramento-San Joaquin Estuary. DAYFLOW program summary. Sacramento, California, USA.

backing plate was approximately 100 g in air and 40 g in water. Transmitters had nominal 2- and 3-yr life spans (75 and 55 pulses/min) and transmitted on unique frequencies in the 48-50 MHz band. Although the time an individual sturgeon would spend in fresh water, where radio tags could be detected, was expected to be relatively brief each year, long-duration tags were selected to attempt to determine spawning periodicity.

White sturgeon were captured with setlines fished overnight in the Sacramento River between Courtland (rkm 56) and Freeport (rkm 74). Most white sturgeon that far upstream are thought to be mature fish moving upstream to spawning areas (Kohlhorst et al. 1991, Miller 1972). Approximately 400 hooks were spread over four 550-m setlines of 6.4-mm diameter soft-lay nylon rope. Initially, 12/0, 14/0, and 16/0 tuna circle hooks were used, but in 1990 they were replaced with 8/0, 10/0, and 12/0 straight shank "O'Shaughnessy" hooks similar to those used in the sport fishery. Hooks were attached to setlines using groundline clips with 1-m braided polyester leaders. Fish were lifted on the deck of the tagging boat with the aid of a soft noose slipped behind the pectoral fins, sexed by external examination, and measured to the nearest cm TL. The external characteristic used to sex sturgeon was abdominal distension; fish with noticeably distended abdomens were assumed to be females (Conti et al. 1988). Radio tags were attached by drilling holes through the base of the fourth and fifth dorsal scutes, slipping the mounting wires through the drilled holes and the PVC backing plate, then fastening the wires together with two crimp fittings. Sturgeon were normally out of the water for 2-3 min.

Fishing was usually conducted Monday through Thursday nights until the annual supply of 30 tags was exhausted. In 1990, every healthy sturgeon captured was tagged, without regard to sex. In 1991, female sturgeon were preferentially tagged.

Because the time from tagging to spawning and subsequent return to salt water was expected to be brief, the tracking strategy was to locate each tagged fish as often as possible. Radio-tagged sturgeon were tracked by automobile, airplane, and boat. Auto searches were effective from Rio Vista (rkm 19) to Verona and from Meridian (rkm 214) to Colusa, but were only partially successful in the remaining upstream reaches of the study area as public roads did not provide continuous access to the river. During auto searches, 8 to 10 frequencies were scanned for 2 s each while driving 45-50 km/h, allowing three opportunities to hear each tag within the 300-500-m reception range. Most auto searches initially proceeded upriver and, as fish were located, scanned frequencies were changed to include fish previously in upriver locations. If a previously known upriver fish was not located, its frequency was scanned in the lower river on the return trip.

Aerial surveys of the Sacramento River for radio-tagged white sturgeon were conducted on 34 d from 1990 to 1993. In late winter and spring 1990, 16 of 17 aerial searches were conducted during CDFG Sacramento River System Sport Fish Catch Inventory flights. All major tributaries in the Sacramento basin available to anadromous fish were searched, including the Feather, Yuba, and American rivers. In one additional flight in 1990, seven flights in 1991, seven flights in 1992, and three flights

in 1993, only the main stem Sacramento River from the downstream limit of fresh water to Ord Ferry Bend was searched.

Early aerial tracking indicated that tags could be detected for 30-50 s at normal flight speeds and altitudes (130-150 km/h, 50-200 m). Therefore, during angler survey flights, only seven to nine frequencies could be scanned for 2 s each by a single observer to allow two to three opportunities to hear a given tag. During dedicated study flights, the river was flown with two observers in both directions allowing up to 32 frequencies to be continuously scanned. One flight in 1991 and all flights in 1992 and 1993 searched for fish tagged in previous years. In 1990-1992, the downstream limit of telemetry observations was reached 5 km below Rio Vista because salt water absorbed radio signals. High freshwater flows in 1993 allowed reception of radio-tag signals as far downstream as 24 km below Rio Vista.

Most boat surveys were in the reach where fish were tagged. Four upriver boat surveys in 1990 and one upriver boat survey in 1991 primarily searched for fish that had disappeared between aerial and auto surveys or were last detected in areas where automobile searches were ineffective.

During auto, aircraft, and boat searches, the primary antenna was a 1/4-wavelength base-loaded whip. When more precise positioning was desired during auto or boat searches, a hand-held, tuned, diamond-loop, directional antenna was used.

Spawning Habitats

To determine spawning locations and sites of egg deposition more precisely than was possible by locating radio-tagged adults and to verify spawning at these specific locations, 0.9 x 0.75-m artificial substrate egg samplers of latex-coated animal hair (McCabe and Beckman 1990) were deployed. Between 16 April and 3 June 1991, two or three artificial substrates were fished across each of 16 transects between Grimes (rkm 201) and Moulton Weir (Appendix 1). Sites initially selected were in areas where local anglers are successful in catching fish (T. Shroyer, CDFG, pers. comm.) or downstream of deep locations, often associated with sharp river bends, where sturgeon had been located during daylight hours while radio tracking. Artificial substrates were examined twice weekly for attached eggs, cleaned of debris, and reset. As the season progressed, transects originally located in depositional areas, where artificial substrates filled with sediment, were moved to erosional or stable areas.

In 1992, substrates were installed at four transects between rkm 223 and rkm 251 on 4 February (Appendix 2). After high flows from mid-February through mid-March washed out or sedimented in artificial substrates at several transects, six transects were re-established upstream of Colusa between rkm 232 and 255 between 20 March and 14 April. These were examined biweekly through 15 May, when two transects were discontinued. All sampling ended on 22 May.

Substrate composition at each site was sampled with a clamshell dredge. Because of the somewhat imprecise nature of dredge sampling, sediments were classified according to the scale developed for the Instream Flow Incremental Methodology

(Bovee and Cochnauer[4] 1977) rather than a more precise particle size distribution (Appendix 3). In 1991, depth was estimated by the amount of buoy line deployed until the substrate hit bottom. In 1992, depth was measured at each site by fathometer and water velocity was measured both at the surface and 30 cm from the river bottom with a propeller-driven, digital flowmeter. To estimate date of spawning, I aged individual eggs according to developmental stage (Beer[5] 1981), with compensation for temperature (Wang et al. 1985), and subtracted this age from sampling time.

Unless otherwise cited, river flow and stage data used in this paper were obtained from the California Data Exchange Center maintained by the California Department of Water Resources.

RESULTS

Migration

Capture and tagging

In 17 fishing days between 29 January and 10 March 1990, 14 adult female, 15 adult male and one subadult (95 cm) white sturgeon were radio tagged. Nineteen of the 30 fish tagged were captured between 6 and 9 March when flows at Freeport increased to 450-510 m^3/s. Previous flows during the fishing period had ranged from 350 to 425 m^3/s. Most fish were caught after circle hooks had been replaced by straight-shank hooks.

In 1991, 21 adult female and seven adult male white sturgeon and one adult white sturgeon of undetermined sex were radio-tagged during 11 fishing days between 4 March and 21 March. A single male green sturgeon was tagged on 7 March. Sturgeon were captured when daily flows at Freeport averaged 695 m^3/s (range: 375-1,070 m^3/s). No fish died during capture and tagging either year.

After tagging, 33 of 58 adult white sturgeon (57%) did not continue their upstream migration. In 1990, 18 of 29 white sturgeon (11 females and seven males) moved downstream either immediately after tagging (four females and four males) or after spending 1-10 d within 10 km of the tagging site (seven females: $\bar{x}$ = 4.1, SD = 2.1; three males: $\bar{x}$ = 4.3, SD = 5.8). Mean TL of females that moved upstream was 181 cm (SD = 5.1); mean TL of females moving downstream was 170 cm (SD = 13.0). For males, the respective TLs were 135 cm (SD = 16.4) and 158 cm (SD = 22.8).

In 1991, 15 of 29 sturgeon moved downstream either (i) immediately after tagging (three females and the white sturgeon of undetermined sex), (ii) after remaining near the tagging site for 1 d (two males), or (iii) after 1-26 d within 10 km of the tagging

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[4] Bovee, K.D. and T. Cochnauer. 1977. Development and evaluation of weighted criteria, probability-of-use curves for instream flow assessments: Fisheries. U.S. Fish and Wildlife Service, Cooperative Instream Flow Services Group, Instream Flow Information Paper No. 3.

[5] Beer, K.E. 1981. Embryonic and larval development of white sturgeon (*Acipenser transmontanus*). M.S. Thesis, University of California, Davis, California, USA.

site (nine females: $\bar{x}$ = 7.1, SD = 9.1). The mean TL of females moving upstream after tagging was 158 cm (SD = 8.5); those that moved downstream averaged 151 cm (SD = 9.5).

Movements, 1990

In 1990, only three radio-tagged females migrated upstream (Table 1, Fig. 2a) after delays of 2-19 d ($\bar{x}$ = 13.0, SD = 9.5). During sustained, active migration, upstream travel rates ranged from 4.6 to 22.3 km/d ($\bar{x}$ = 13.8, SD = 8.9). A 182-cm female tagged on 30 January resumed an upstream migration 2 d after tagging (Fig. 2a), reaching a maximum recorded ascension of rkm 220 on 7 March. This fish was last located 45 h later downstream at rkm 137. It was not found in the lower river during ground searches the following 2 d. A 175-cm female tagged on 14 February (Fig. 2a) remained near the tagging site for 18 d, then moved upstream strongly during a slight rise in river flow, reaching rkm 179 on 9 March. Twenty-seven h later, it was found at rkm 103 moving downstream at a velocity estimated to be approximately equal to that of the river current. The third female (185 cm TL) tagged on 23 February (Fig. 2a), dropped downstream to rkm 21 eleven d after tagging, then moved back up into the tagging area. It resumed a definite upstream migration 19 d after tagging, reaching rkm 180 during initial upstream movement. After 16 d near this location, this fish resumed slow upstream movement and reached Colusa (rkm 233) in 2 weeks. It remained near Colusa for 1 month, then, between 24 May and 26 May, was tracked moving downstream as fast as 91 km/d, leaving the river within 3 d. This rapid downstream movement was preceded by a slight increase (22 m^3/s) in river flow at Colusa between 17 and 23 May.

Eight males made upstream migrations after tagging in 1990 following delays of 0-13 d ($\bar{x}$ = 4.0, SD = 4.3) (Table 1; Fig. 2b, c). Maximum ascension ranged from rkm

Table 1. Summary of white sturgeon upstream movements following tagging in 1990. Actual movements are shown in Fig. 2. F = female, M = male, rkm = river kilometer.

Total length (cm) and sex	Tagging date	Tagging location (rkm)	Migration delay (days)	Upstream limit of initial migration (rkm)	Date	Average upstream movement (km/d)	Ultimate maximum ascention (rkm)
182 F	30 Jan	63	2	220	7 Mar	4.6	220
175 F	14 Feb	63	18	179	9 Mar	22.3	179
160 M	21 Feb	69	5	113	2 Mar	7.2	113
127 M	21 Feb	69	13	106	10 Mar	9.1	106
185 F	23 Feb	68	19	182	23 Mar	14.7	234
144 M	7 Mar	66	0	248	24 Mar	10.7	248
116 M	7 Mar	66	6	183	24 Mar	10.4	191
129 M	9 Mar	64	4	212	21 Mar	19.1	212
157 M	9 Mar	64	1	142	16 Mar	19.2	157
121 M	9 Mar	64	0	230	19 Mar	16.9	233
129 M	9 Mar	64	3	188	21 Mar	11.2	188

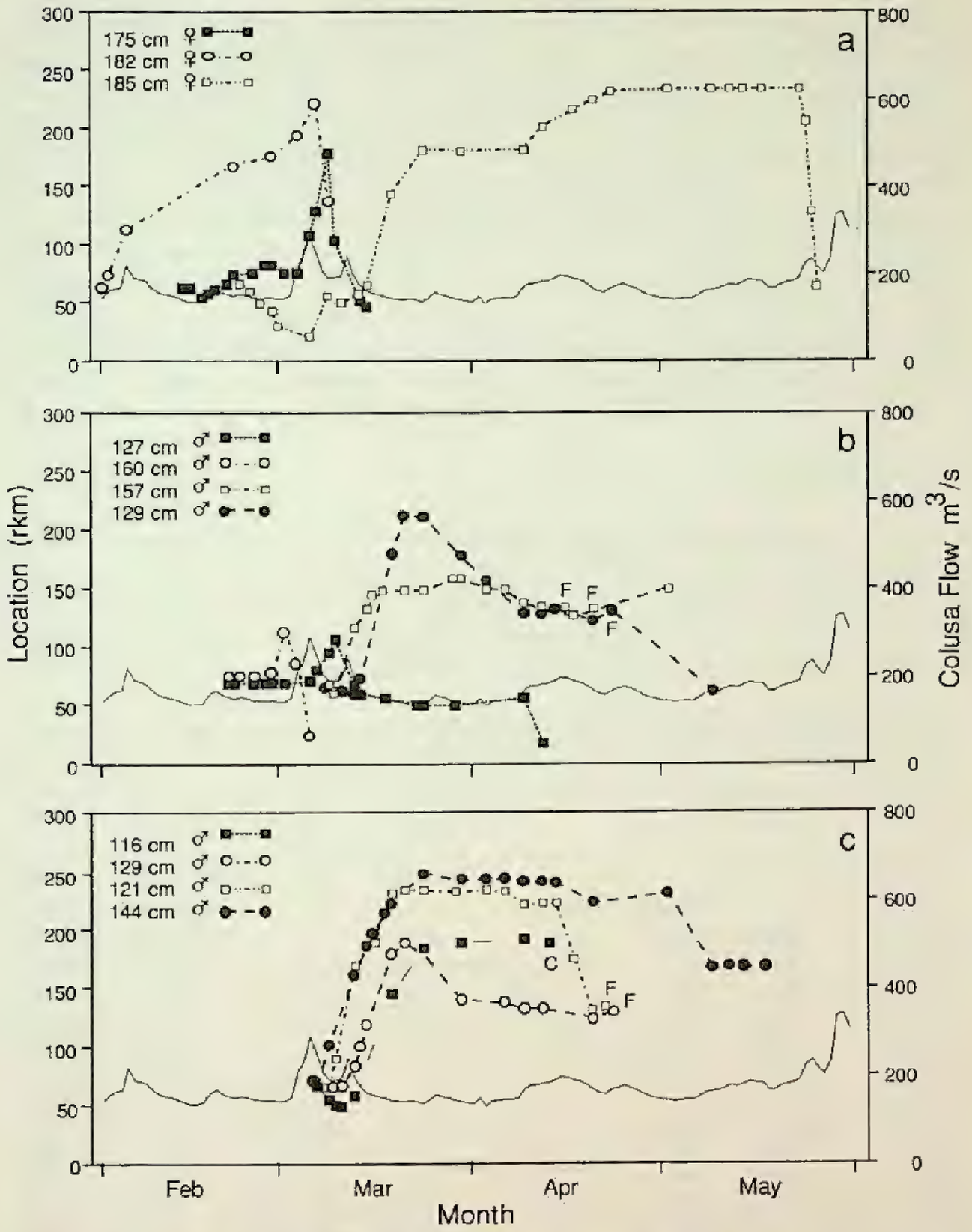

Figure 2. White sturgeon movements following 1990 tagging and Sacramento River flow at Colusa (solid line). Markers indicate observations; some observations have been deleted for clarity. "C" indicates the point of angler capture, if applicable. "F" indicates a location in the lower Feather River.

106 to 248, and upstream migration rates averaged 13.0 km/d (SD = 4.7, range = 7.2-19.1) during initial active migrations. Although some males made

apparently rapid downstream movements or disappeared from upstream locations between tracking surveys, no male was repeatedly located on a daily (or more frequent) basis while migrating downstream, so no downstream migration rate comparable to that observed for females was determined. In contrast to females, several males drifted irregularly downstream after reaching their maximum ascension point (Fig. 2b, c). Four males that had moved downstream below Verona were found in the Feather River 1-5 km upstream from its mouth between 14 April and 2 May when reservoir releases increased Feather River flow above that in the Sacramento River upstream of Verona (Fig. 2b, c). A 116-cm male (Fig. 2c) was caught by an angler on 13 April at rkm 179 after moving upstream. A 144-cm male (Fig. 2c), tagged on 7 March, moved rapidly upstream to rkm 248, remained near that location for at least 20 d, then drifted downstream to rkm 168, where it remained for 2 weeks. Sometime after 17 May, this tag was shed at that location, $\geq$ 73 d after capture.

Movements, 1991

In 1991, nine females resumed their upstream migration after delaying near the tagging site for 0-11 d ($\bar{x}$ = 2.4, SD = 3.9) (Table 2). Upstream migration rates ranged from 5.8 to 25.2 km/d ($\bar{x}$ = 11.5, SD = 6.8). Five females either moved back downstream (Fig. 3a) or were last located upstream during elevated flows in March. Those last located upstream in March are presumed to have moved rapidly downstream

Table 2. Summary of white and green sturgeon upstream movements following tagging in 1991. Actual movements are shown in Figure 3. Where migration delay is unknown, the migration rate is calculated from the day of tagging. F = female, M = male, rkm = river kilometer.

Total length (cm) and sex	Tagging date	Tagging location (rkm)	Migration delay (days)	Upstream limit of initial migration (rkm)	Date	Average upstream movement (km/d)	Ultimate maximum ascention (rkm)
175 F	7 Mar	70	11	124	21 Mar	25.2	124
125 M	7 Mar	60	unk	164	22 Mar	9.0	164
184 M[a]	7 Mar	60	unk	108	13 Mar	8.0	108
147 M	8 Mar	66	1	266	22 Mar	14.3	293
142 M	8 Mar	62	0	221	22 Mar	11.4	233
155 F	12 Mar	69	0	213	29 Mar	8.5	213
146 F	13 Mar	66	0	122	20 Mar	7.9	128
130 F	14 Mar	70	2	149	29 Mar	6.1	149
187 F	14 Mar	66	7	154	29 Mar	10.8	154
146 F	16 Mar	62	1	219	3 April	9.8	219
188 F	19 Mar	66	1	188	26 Mar	20.2	188
152 F	19 Mar	70	0	113	24 Mar	8.5	116
133 M	19 Mar	58	unk	109	28 Mar	5.7	109
138 M	20 Mar	64	unk	124	4 April	10.4	124
144 F	21 Mar	66	0	113	29 Mar	5.8	136

[a] Green Sturgeon

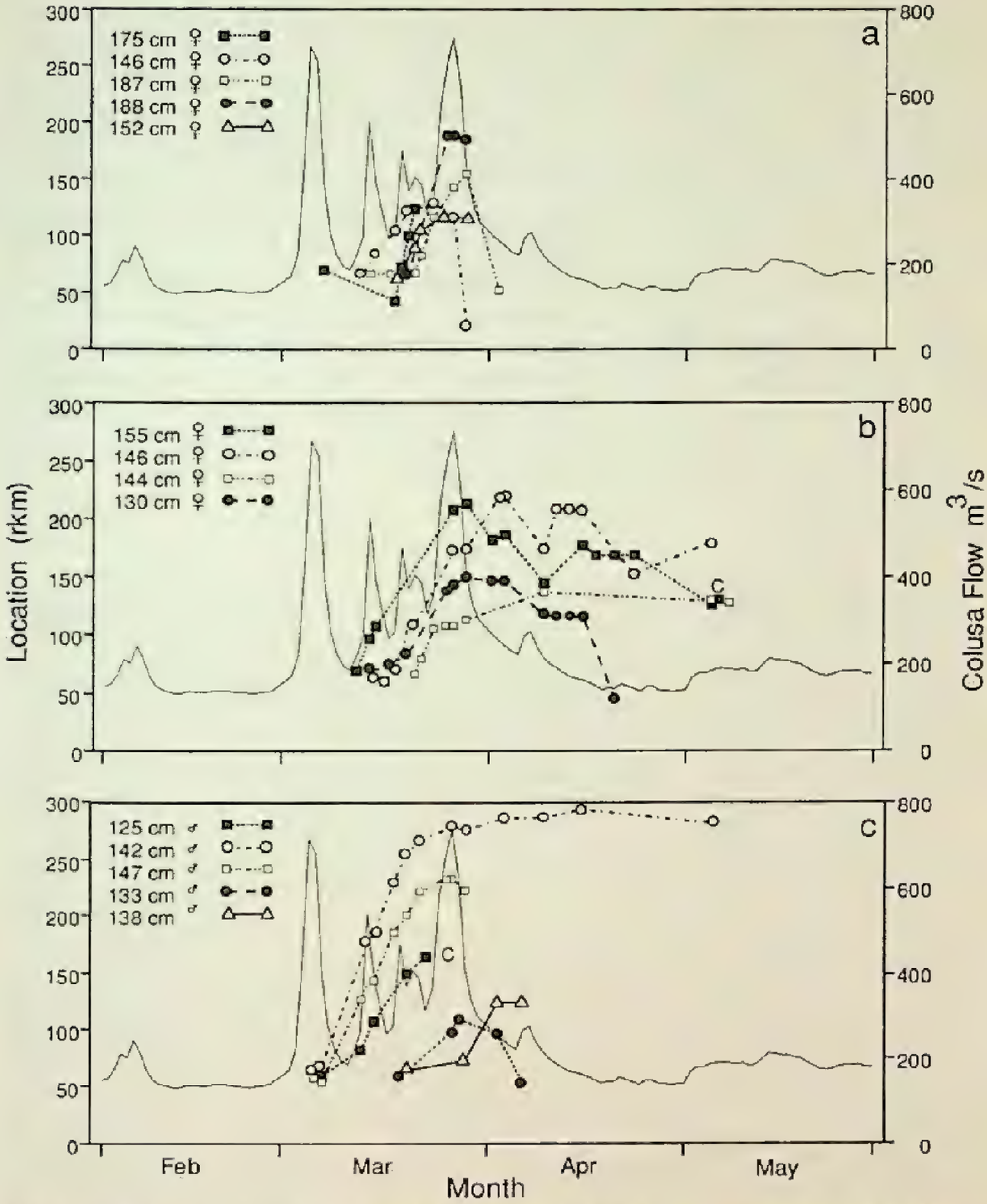

Figure 3. White sturgeon movements following 1991 tagging and Sacramento River flow at Colusa (solid line). Markers indicate observations; some observations have been deleted for clarity. "C" indicates the point of angler capture, if applicable.

without being detected between tracking surveys. Of the four females remaining upriver after the March flow peaks, three were still upriver on the last aerial tracking survey on 6 May; one had moved downriver and was last found below the tagging site in mid-April (Fig. 3b). On 7 May, a 155-cm female was caught within 1 km of its 6 May location by an angler who affirmed the fish was a gravid female.

Migration behavior of a 184-cm male green sturgeon and three male white sturgeon were not measured because the tagging area was not searched daily (Table 2). One male white sturgeon (142 cm) was found upstream of the tagging location the day after tagging and one other (147 cm) moved upstream after a 1-d delay, during which it drifted 7 km downstream (Fig. 3c). Upstream migration rates for two male sturgeon for which departure dates from the tagging area are known ranged from 11.4 to 14.3 km/d ($\bar{x}$ = 12.9, SD = 2.1). The male green sturgeon was only observed once (at rkm 107, 7 d after tagging) despite repeated air and ground searches of the Sacramento River and lower 10 km of the Feather River. A 125-cm male (Fig. 3c) was caught by an angler at rkm 164, apparently still actively migrating upstream. Two males moved upstream of Colusa (Fig. 3c), one ultimately ascending to rkm 293, the most upstream location of any tagged fish in the 2-yr study. It remained upriver through the last aerial survey on 6 May. Again, as in 1990, no males were repeatedly observed on a daily basis while migrating downstream and no comparison could be made with downstream migration rates of females.

Tag Shedding

In addition to the previously mentioned shed tag, at least six other tags are known to have been shed. Shed tags could be differentiated from tags on relatively stationary fish by the consistency of signal strength; tags still attached to a sturgeon tended to vary in signal strength as the orientation of the transmitting antenna changed, while signal strength of shed tags was unvarying. In 1990, tags applied to a 95-cm immature fish and a 149-cm female, neither of which ascended very far upstream of the tagging area, were repeatedly located near Rio Vista 120 and 35 d, respectively, after tagging. The tag applied to a 127-cm male in February 1990, which was tracked moving up to the Verona area and then downstream (Fig. 2a), was found in February 1991 at rkm 69 near the north end of the tagging area. This fish was not found in an aerial search of the river on 3 June 1990; presumably, it re-entered the river after that date. Tags applied to a 175-cm female in February 1990 (Fig. 2a) and to a 129-cm male (Fig. 2b) in 1991 were both repeatedly located 23 km downstream from Rio Vista in March and April 1993 when high outflows freshened this downstream area sufficiently to allow reception of radio signals. The tag applied to a 188-cm female (Fig. 3a) in March 1991 was recovered from a beach 35 km downstream of Rio Vista in June 1992 with the tagging harness intact. Barnacles on the tag indicate it was in salt water for some time before being recovered. All shed tags continued to transmit to the end of their 2- or3-yr life spans. No tags except these shed tags were detected during the 1992 and 1993 flights.

Spawning habitats

Between 7 and 14 May 1991, nine eggs were collected on artificial substrates at two locations near Colusa (Table 3). I estimated, based on degree of embryological development, that these eggs were spawned on 4 different d between 6 and 13 May. These spawnings followed a 40 m^3/s increase in Sacramento River flows at Colusa,

Table 3. Date, location, and developmental stage of sturgeon eggs collected on artificial substrates in the Sacramento River in 1991.

Date collected	Location (rkm)	Developmental stage	Estimated age (h)	Estimated spawning date
7 May	234.2	2 Yolk plug	30-36	5-6 May
10 May	222.9	3 Neurulation complete	55-70	7-8 May
		1 Decomposed	—	—
14 May	222.9	1 Neurulation complete	55-70	11 May
		1 Yolk plug	30-36	13 May
		1 Decomposed	—	—

which had averaged 145 m^3/s from the beginning of sampling through 2 May (Fig. 4a). This increase in flow was due to increased reservoir releases rather than precipitation. During these spawnings, average daily river flow ranged from 184 to 188 m^3/s and temperatures ranged from 14 to 17°C; highest temperature was measured on 7 May. Seven of the eggs were taken immediately downstream from a deep (> 8 m) pool formed where the river makes a right-angled bend (rkm 222.9). The sample transect was approximately 20 m below the downstream end of this pool. Transect depth ranged from 1.5 to 2.5 m. Substrates were sand to gravel-sand mixtures. Eggs with intact egg membranes from this site were either evenly covered with sand grains, suggesting that they had contacted the river bottom before becoming trapped in the artificial substrate, or were noted in laboratory examination to be 3/4 covered with sand, suggesting that sediment adhesion occurred after the eggs became entrapped on the substrate.

Between 24 March and 21 April 1992, 32 eggs were collected at two transects; these eggs represented at least six spawning events (Table 4). During these spawnings, river flow ranged from 180 m^3/s to 350 m^3/s (Fig. 4b) and temperatures ranged from 12 to 16°C. As in 1991, spawning seemed to be stimulated on 15 and 17 April by a small increase in flow starting on 13 April, following a period of relatively low and declining flows. Sturgeon eggs were taken from substrates placed at depths from 1.8 to 4.6 m where bottom flow velocities exceeded 1.0 m/s (Fig. 5). All eggs were collected over bottoms which were primarily gravel and cobble. As in 1991, eggs were 40-100% sand covered.

DISCUSSION

The externally attached radio tags worked well over the short duration of a single spawning season and only one tag was shed while a fish was in the spawning area. However, my attempt to assess spawning periodicity by using long-duration telemetry tags was not successful because of tag shedding. Kieffer and Kynard (1993) found that external telemetry tags were unsatisfactory for long-term studies of shortnose sturgeon

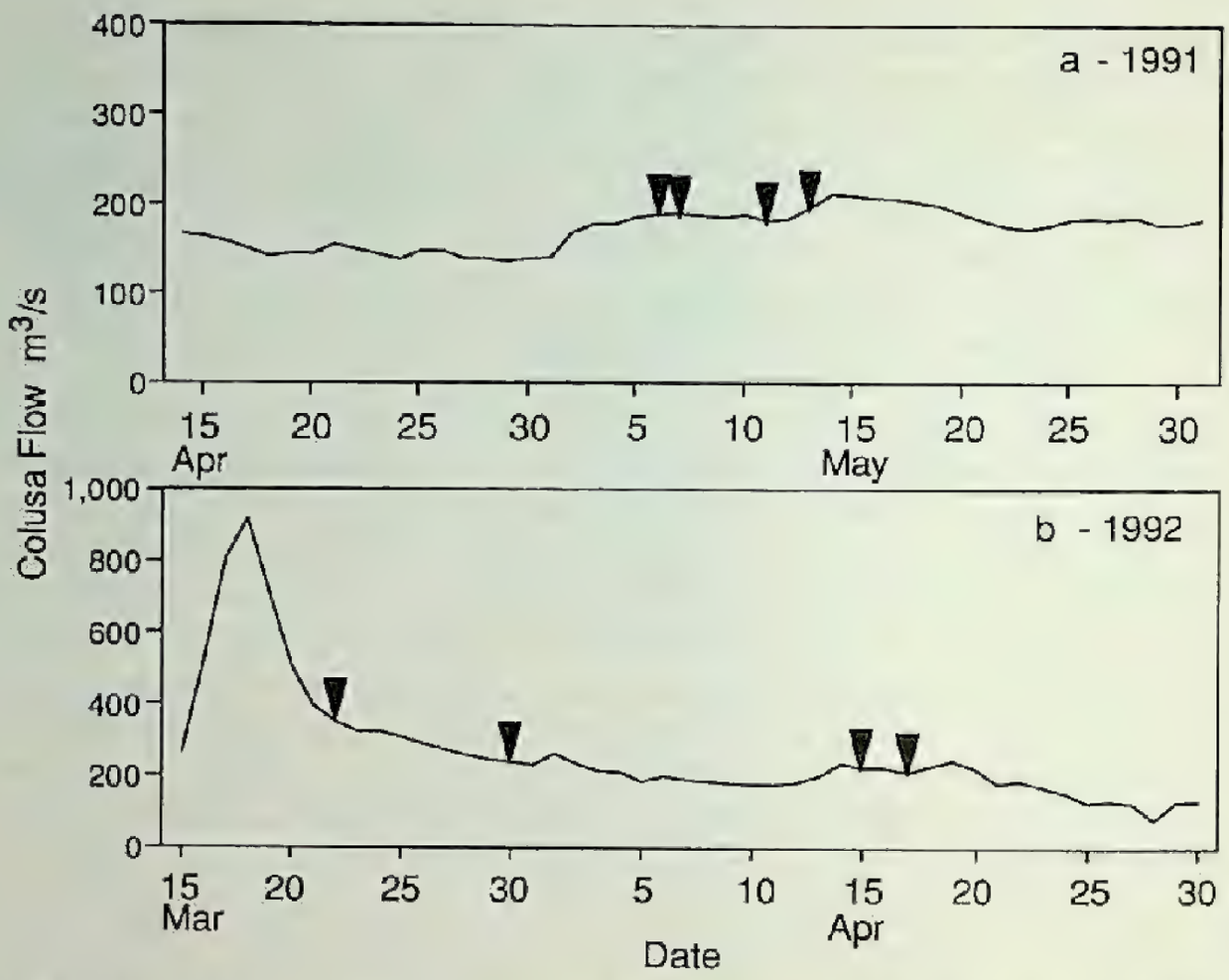

Figure 4. Estimated spawning dates (arrows) and Sacramento River flows at Colusa in 1991 and 1992.

Table 4. Date, location, and developmental stage of sturgeon eggs collected on artificial substrates in the Sacramento River in 1992.

Date collected	Location (rkm)	Developmental stage	Estimated age (h)	Estimated spawning date
24 March	251.2	1 Yolk plug	30-36	22-23 March
31 March	251.2	1 Gastrulation	18-24	30 March
17 April	252.2	4 Early cleavage	6-8	17 April
		1 Early neurulation	40-48	15 April
17 April	251.2	8 Early cleavage	6-8	17 April
		15 Late yolk plug-early neurulation	30-40	15 April
21 April[a]	251.2	2 S-heart	70-90	17 April

[a] Eggs were present on substrates on 17 April and missed during examination.

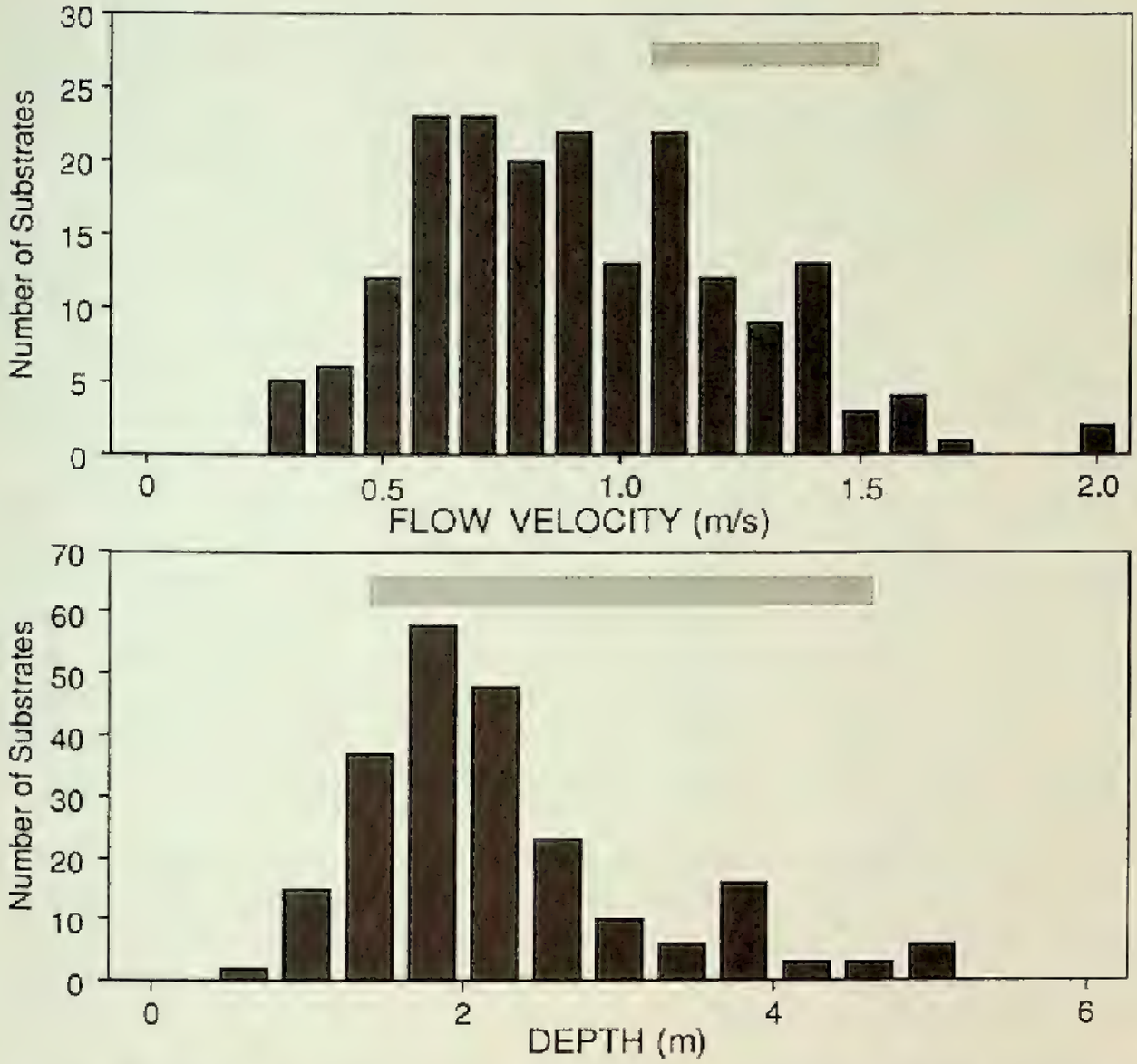

Figure 5. Distribution of bottom flow velocities (measured 30 cm above the substrate) and depths sampled with artificial substrates in the Sacramento River in 1991 and 1992. Shaded horizontal bars denote the range of velocities and depths where eggs were collected.

in the Merrimack River because all externally affixed transmitters were shed 14-134 d after release. Similarly, Moser and Ross (1995) found that seven juvenile (69-122 cm) Atlantic sturgeon (*A. oxyrhynchus*) retained external tags only 36-229 d. The shortest term of tag retention in my study was < 32 d; the longest verified term was 92 d. While delayed mortality after tagging could mimic a shed tag, the extreme tolerance of shortnose sturgeon to repeated gill-net capture and tagging suggests that fish of the genus *Acipenser* withstand handling and radio-tagging well (Kieffer and Kynard 1993).

Many sturgeon abandoned their upstream migrations after tagging and others interrupted their migration before proceeding upstream. Twenty-three of 35 female white sturgeon tagged either moved downstream immediately after tagging or after spending up to 26 d in the vicinity of the tagging site. This behavior was most likely due to stress induced by capture and tagging. In sturgeon aquaculture, 30-40% of ripe

females collected from the wild for spawning fail to progress to final oocyte maturation in the hatchery because of capture stress (Conte et al. 1988). Moser and Ross (1995) also noted that excessively handled shortnose sturgeon moved rapidly downstream. Although my capture and tagging techniques were designed to minimize stress, undoubtedly my tagging was of some detriment to the fish.

It is also possible that some sturgeon were moving upriver for reasons other than spawning. From angler recaptures of white sturgeon tagged for population and mortality estimates, it is known that some sturgeon move into the lower Sacramento River from downstream portions of the estuary during fall (Miller 1972, Kohlhorst et al. 1991). Some of these fish, presumably mature and ready to spawn, move up the river, concentrating between Verona and Colusa. Both Miller and Kohlhorst et al. concluded that these fish were spawners because the mean length at tagging of fish recaptured by anglers upstream of Verona was significantly larger than the overall recapture sample. Through 1992, mean size at time of tagging of sturgeon recaptured upstream of Verona (139 cm) was significantly larger than the remainder of the recapture sample (125 cm) ($t = 8.96$, 1,776 df, $P < 0.001$). Conversely, mean length of sturgeon recaptured by anglers in the area where sturgeon were radio-tagged (Courtland to Verona) was 140 cm at time of tagging, not significantly different from recaptures above Verona ($t = 0.46$, 102 df, $P > 0.5$) (CDFG, unpubl. data). This suggests that most white sturgeon in the tagging capture area are migrants on their way to the spawning area upstream.

A third possible reason for apparent abandonment of spawning is that my sample may have included spent fish on their way downstream. This is most applicable to the sturgeon identified as males and may explain why "male" sturgeon that moved downstream after tagging (identified as males, but really females) tended to be larger than males that moved upstream.

The responses of sturgeon to changes in river flow in the dry winter and spring of 1990 may provide some insight into the minimum flow needs of white sturgeon in the Sacramento River. Prespawning adults tended to move upstream during periods of elevated flow. When Colusa flows decreased below 150 m^3/s, fish tended to cease their upstream migration or to drift downstream (Fig. 2). In 1991, this tendency was less distinct, probably because flows were higher during tagging and a greater portion of the tagged fish left the system during elevated flows in March and early April. Two females (Fig. 3b) did respond to a small flow pulse of 275 m^3/s on 7-8 April by moving upstream, then drifted downstream when flows dropped below 150 m^3/s between 18 April and 2 May.

Flow increases above low base levels may trigger spawning. In both 1991 and 1992, no spawning was detected by artificial substrate sampling in periods when mean daily flows were < 180 m^3/s; sturgeon spawned 1-3 d after flows increased above that level. Kieffer and Kynard (1993) also noted downstream migrations of shortnose sturgeon from the spawning area concurrent with pronounced increases in flow in the Merrimack River. Kohlhorst (1976) stated that there was no obvious flow threshold in the Sacramento River at which spawning was initiated, but in late winter and spring 1973, when his larva sampling was conducted, flows upstream of Colusa ranged from

> 2,000 m^3/s in February to 300 m^3/s in late April and early May, much higher than the low flows of the drought years of 1991 and 1992.

My data suggest that downstream movement from the spawning area > 50 km/d may be common post-spawning behavior of female white sturgeon in the Sacramento River. Two females that were repeatedly tracked as they migrated downstream were moving at approximately the velocity of floating objects, suggesting a rather passive, but rapid, downstream migration. Similar rapid downstream movement following spawning has been noted for shortnose sturgeon spawning in the Connecticut and Delaware rivers (Buckley and Kynard 1985, O'Herron et al. 1993). Female sturgeon oocyte maturation and ovulation is preprogrammed by a release of pituitary gonadotropin and, once mature, eggs are viable only for a few hours (Conte et al. 1988). Hence, female sturgeon spawning is singular within a season and of relatively brief duration. A rapid outmigration is also suggested by three females that disappeared from the Sacramento River in the 2 or 3 d between repeated searches in March 1991. These rapid downstream movements or disappearances also coincided with or followed flow peaks or rises and occurred when Colusa flows were above the 180 m^3/s minimum flow when spawning was detected by egg capture. While completion of spawning is suspected as the cause of apparent rapid departures from the river, either unreported angler capture or equipment failure cannot be excluded as possible causes.

If the maximum ascension of female white sturgeon, or their last location before disappearing, corresponded to the approximate spawning location, then my results generally confirm previous findings suggesting that most white sturgeon spawning in the Sacramento River occurs from Knights Landing to several kilometers above Colusa (Kohlhorst 1976). This result is contrary to expectations because the river between Knights Landing and Colusa generally does not have the larger substrate material associated with sturgeon spawning areas (Gard[6] 1996), although the banks are often lined with cobble and larger rip-rap.

A difference from earlier findings is that, based on the movements of two female white sturgeon in 1991 (152 and 146 cm) (Fig. 3a) which were never found above Verona, some spawning potentially occurs below the Feather River. Sturgeon spawning below the Feather River has not been verified by egg capture, but numerous wing dams have been constructed of pilings and large rocks to reduce shoaling in the river between Verona and Sacramento. These dams may provide suitable sturgeon spawning habitat.

ACKNOWLEDGMENTS

This work was supported by Federal Aid in Sport Fish Restoration Act funds, Grant F-51-R. M. Silva, E. Santos, S. Waller and C. Hagen aided in capture, tagging, and tracking sturgeon and fishing artificial substrates. D. Kohlhorst provided analytical and editorial guidance. Special thanks to R. Cole, R. VanBenthuysen, R. Morgan, and J. Veal, Warden-Pilots of CDFG's Air Services Unit.

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Appendix 1. Artificial substrate sampling sites, 1991.

Location (river km)	Dates Sampled	Depth range (meters)	Substrate type[a] Right	Center	Left
202.5	19 Apr - 31 May	0.9 - 4.6	4.0	4.0	6.0
205.2	16 Apr - 26 Apr	2.7 - 3.0	4.0	4.0	4.0
206.2	16 Apr - 23 Apr	4.5 - 6.0	6.0	hard[b]	NS[c]
207.3	16 Apr - 3 June	0.9 - 3.0	4.0	4.1	5.0
211.1	16 Apr - 19 Apr	1.1 - 2.4	4.0	4.0	4.7
222.9	16 Apr - 3 June	0.9 - 3.7	4.0	4.7	4.7
232.1	1 May - 3 June	1.5 - 7.0	6.0	4.0	4.0
234.2	26 Apr - 31 May	0.9 - 3.6	4.2	hard[b]	6.0
237.5	16 Apr - 26 Apr	1.0 - 3.7	4.1	4.0	4.5
238.2	29 Apr - 31 May	0.6 - 4.6	hard[b]	4.0	4.6
239.1	16 Apr - 19 Apr	2.1 - 5.5	4.0	4.0	4.5
243.8	16 Apr - 23 Apr	1.5 - 5.5	6.0	4.0	4.5
244.6	26 Apr - 3 May	0.9 - 1.5	4.7	4.9	5.0
245.1	17 May - 3 June	1.5 - 2.5	4.7	4.9	5.0
245.4	16 Apr - 23 Apr	3.0 - 4.6	4.0	4.0	4.0
249.0	19 Apr - 14 May	0.6 - 4.6	4.5	4.8	6.0

[a] According to Instream Flow Incremental Methodology.
[b] Only material dredged was a small amount of sand; substrate was either bedrock or very hard clay.
[c] Not sampled

Appendix 2. Artificial substrate sampling sites, 1992.

Location (river km)	Dates Sampled	Depth range (meters)	Substrate type[a] Right	Center	Left
223.5	4 Feb - 11 Feb	2.1 - 2.4	NS	NS	NS
232.4	4 Feb - 22 May	1.2 - 3.0	4.5	4.5	4.0
244.2	7 Apr - 15 May	2.3 - 3.7	4.2	4.5	5.5
246.0	4 Feb - 11 Feb	1.3 - 2.8	4.0	4.0	4.0
251.2	4 Feb - 22 May	0.8 - 5.2	5.0	5.0	5.0
252.2	7 Apr - 15 May	1.5 - 2.6	4.0	5.0	5.0
252.7	20 Mar - 19 May	1.1 - 3.4	4.0	4.0	5.0
254.4	24 Mar - 19 May	0.9 - 3.4	5.0	5.0	5.0

Appendix 3. Substrate classifications developed for the Instream Flow Incremental Methodology. To describe a mixture of adjacent materials, the smaller material is listed with a decimal denoting the portion of larger material, e.g., 4.7 denotes a mixture of 30% sand and 70% gravel.

Code	Substrate	Particle size (mm)
1	Plant detritus/organic material	—
2	mud/soft clay	—
3	silt	<0.062
4	sand	0.062 - 2.0
5	gravel	2.0 - 64
6	Cobble/rubble	64 - 250
7	Boulder	250 - 4,000
8	Bedrock	—

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RELATIVE IMPORTANCE OF PREY ITEMS TO CALIFORNIA HALIBUT

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The relative importance of prey items in the diet of California halibut, *Paralichthys californicus*, was determined from 1,397 stomachs taken from fish ranging from 159 to 1055 mm total length (TL). Northern anchovy, *Engraulis mordax*, and mysids were the most important taxa in halibut < 300 mm TL. Halibut ≥ 300 mm TL were predominately piscivores, feeding on Pacific sardine, *Sardinops sagax*; northern anchovy; and white croaker, *Genyonemus lineatus*.

INTRODUCTION

California halibut, *Paralichthys californicus*, is a nearshore species that ranges from Magdalena Bay, Baja California to the Quillayute River, Washington (Miller and Lea 1972, Eschmeyer et al. 1983) and is a valuable commercial and sport fish in California (Schott 1971, Barsky 1990, Jow 1990).

Young California halibut are found in protected bays and estuaries; extensive research has been done on the feeding behavior and prey preference of juvenile halibut in these habitats (Haaker 1975, L.G. Allen 1988, Drawbridge[2] 1990). California halibut < 55 mm standard length (SL) feed predominately on small crustaceans (harpacticoid copepods, small gammarid amphipods, and mysids), while halibut between 55 and 230 mm SL feed increasingly on small fish, such as gobies; topsmelt, *Atherinops affinis*; and California killifish, *Fundulus parvipinnis* (Haaker 1975, L.G. Allen 1988). As juvenile California halibut increase in size and migrate out of protected bays and estuaries, they select larger and quicker prey (Drawbridge[2] 1990).

This trend towards larger and quicker prey continues among the larger California halibut found in open coastal waters. Large juvenile and young adult halibut (245-300 mm SL) have been found to forage predominately on northern anchovy, *Engraulis mordax*, and mysids (M.J. Allen[3] 1982, Roberts et al. 1982, Plummer et

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al. 1983, Kramer and Sunada 1992). When northern anchovies are scarce, juvenile halibut feed selectively on the larger mysid, *Neomysis kadiakensis*, even though the smaller mysid, *Metamysidopsis elongata*, may be 28 times more abundant (Roberts et al. 1982, Plummer et al. 1983). Although California halibut > 300 mm SL have been found to prey on a variety of larger nearshore species, northern anchovy dominate their stomach contents by both number and frequency of occurrence (M.J. Allen[3] 1982, 1990; Plummer et al. 1983).

Previous studies of California halibut diet examined a relatively small number of stomachs and included few halibut > 500 mm SL. This study re-examines the diet of California halibut from a large sample over a wide size range.

METHODS

Stomachs were collected during two cruises designed to assess the biomass of California halibut from the United States-Mexico border north to Bodega Bay, California. The first cruise was during July and August 1993, from Point Arguello to Bodega Bay. The second cruise took place during February and March 1994, from the United States-Mexico border to Point Arguello. Cruise dates were chosen to coincide with the peak period of halibut spawning activity in each region.

A 400-mesh Eastern trawl (15 m wide x 1.5 m high, 10.2 cm stretch mesh body, 8.9 cm stretch mesh cod end) was used to collect California halibut. Trawls were conducted between 0600 and 1800 each day along isobaths at predetermined, randomly selected stations within three depth strata: 0-40 m, 41-80 m, and 81-120 m.

Immediately following each tow, halibut were measured (total length) and macroscopically sexed. Stomachs were clipped posterior to the esophagus and anterior to the pyloric cecum prior to removal. To reduce further digestion, each stomach was injected with a 10% buffered formalin-seawater solution and stored in a freezer aboard the research vessel.

In the laboratory, stomach contents were identified to the lowest possible taxon. Clothier (1950), Miller and Lea (1972), and a reference collection of fish otoliths (sagittae) were used to identify partially digested fish. Prey items were analyzed by frequency of occurrence (F), numbers of items (N), and volumetric displacement (V). These values were summed, converted into percentages, and used to calculate an Index of Relative Importance (IRI): IRI = (%N + %V) %F (Pinkas et al. 1971).

Index of Relative Importance values were used to rank the importance of individual prey items in the diet of California halibut. Ontogenetic changes in diet were estimated by ranking prey for each 100-mm size interval (range 200-1099 mm). The largest fish (800-1099 mm) were combined due to their small numbers, resulting in a total of seven size classes.

RESULTS

We collected 1,408 California halibut (156-1055 mm) during the two research cruises. Of 1,397 stomachs examined, 429 (31%) contained prey.

Table 1. Food items of California halibut ranked by Index of Relative Importance (IRI).

	Length group							
	200-299	300-399	400-499	500-599	600-699	700-799	800-1099	Total
Stomachs with food	52	117	93	87	50	15	15	429
Osteichthyes								
Unidentifiable remains	1441	4988	4902	5578	3753	1853	2680	3233
Pacific sardine		843	368	47	278	93		212
Northern anchovy	142	127	132	127	53	671	264	128
White croaker		2	9	66	177	864	1850	100
Sanddab	259	24	2	21			209	29
Basketweave cusk-eel	21	1	26	81				13
Chub mackerel					478			12
Longspine combfish, *Zaniolepis latipinnis*				3	7			1
Pink seaperch, *Zalembius rosaceus*		4	5					1
Jack mackerel					14			<1
Queenfish, *Seriphus politus*						78		<1
California lizardfish, *Synodus lucioceps*			6					<1
Rockfish, *Sebastes spp.*			3		6			<1
Unidentified sculpin				1				<1
English sole, *Pleuronectes vetulus*		1						<1
Total	1863	5990	5453	5924	4766	3559	5003	3729
Crustacea								
Unidentifiable remains	2015	4	11	5			29	62
Blackspotted bay shrimp	91	50	2					17
Unidentified mysid	102	10						5
Ridgeback rock shrimp			1	6				<1
Unidentified shrimp, *Natantia*	4					35		<1
Mantis shrimp, *Hemisquilla ensigera*		1						<1
Xantus swimming crab, *Portunus xantusii*	3							<1
Total	2215	65	14	11		35	29	84
Mollusca								
California market squid		3	75	260	79	128	29	91
Unidentified cephalopod		2	6					1
Unidentified bivalve, Veneroida		1						<1
Total		6	81	260	79	128	29	92

Table 2. Food items of California halibut ranked by percent numeric occurrence.

	Length group							
	200-299	300-399	400-499	500-599	600-699	700-799	800-1099	Total
Osteichthyes								
Unidentified remains	15.9	55.7	55.2	59.8	50.9	36.8	48.0	47.1
Pacific sardine		14.8	11.5	3.1	16.4	5.3		8.3
Northern anchovy	4.9	5.7	8.3	8.2	5.5	26.3	24.0	8.1
White croaker		0.8	1.0	4.1	7.3	10.5	12.0	3.4
Sanddab	6.1	3.2	1.0	2.1			8.0	3.2
Basketweave cusk-eel	2.4	0.8	3.1	5.2				2.2
Chub mackerel					9.1			1.0
Pink seaperch		0.8	1.0					0.4
Longspine combfish				1.0	1.8			0.4
Rockfish			1.0		1.8			0.4
Jack mackerel					1.8			0.2
Queenfish						5.3		0.2
California lizardfish			1.0					0.2
Unidentified sculpin				1.0				0.2
English sole		0.8						0.2
Total	29.3	82.6	83.1	84.5	94.6	84.2	92.0	75.3
Crustacea								
Unidentified remains	45.1	2.5	3.1	2.1			4.0	9.1
Unidentified mysid	18.3	5.7						4.4
Blackspotted bay shrimp	4.9	5.7	1.0					3.6
Ridgeback rock shrimp			1.0	2.1				0.6
Unidentified shrimp, *Natantia*	1.2					5.3		0.4
Mantis shrimp		0.8						0.2
Xantus swimming crab	1.2							0.2
Total	70.7	14.7	5.1	4.2		5.3	4.0	18.5
Mollusca								
California market squid		0.8	9.4	11.3	5.5	10.5	4.0	5.5
Unidentified cephalopod		0.8	2.1					0.6
Unidentified bivalve, Veneroida		0.8						0.2
Total		2.4	11.5	11.3	5.5	10.5	4.0	6.3

As a taxonomic group, Osteichthyes was the most important diet component for California halibut ≥ 300 mm (Table 1). California halibut from 300 to 399 mm fed predominately on small flatfish (Pacific sanddab, *Citharichthys sordidus*, and speckled sanddab, *Citharichthys stigmaeus*); northern anchovy; and Pacific sardine, *Sardinops sagax* (Tables 2, 3, and 4). The basketweave cusk-eel, *Ophidion scrippsae*, and white croaker, *Genyonemus lineatus*, replaced small flatfish in relative importance

Table 3. Food items of California halibut ranked by percent frequency of occurrence.

	Length group							
	200-299	300-399	400-499	500-599	600-699	700-799	800-1099	Total
Osteichthyes								
Unidentified remains	24.1	59.1	61.5	60.9	52.2	43.8	40.0	51.4
Pacific sardine		15.7	10.8	3.3	12.4	6.3		8.4
Northern anchovy	7.4	6.1	7.2	6.5	4.2	18.8	6.7	6.5
Sanddab	9.3	3.4	1.2	2.2			13.3	3.7
White croaker		0.9	1.2	4.3	8.3	12.5	26.7	3.7
Basketweave cusk-eel	3.7	0.9	3.6	4.3				2.3
Chub mackerel					10.4			1.2
Longspine combfish				1.1	2.1			0.5
Pink seaperch		0.9	1.2					0.5
Rockfish			1.2		2.1			0.4
Jack mackerel					2.1			0.2
Queenfish						6.3		0.2
California lizardfish			1.2					0.2
Unidentified sculpin				1.1				0.2
English sole		0.9						0.2
Total	44.5	88.1	89.1	83.7	93.8	87.7	86.7	79.4
Crustacea								
Unidentified remains	40.7	1.7	3.6	2.2			6.7	6.7
Blackspotted bay shrimp	5.6	5.2	1.2					4.0
Unidentified mysid	5.6	1.7						1.2
Ridgeback rock shrimp			1.2	2.2				0.7
Unidentified shrimp, *Natantia*	1.9					6.3		0.5
Mantis shrimp		0.9						0.2
Xantus swimming crab	1.9							0.2
Total	55.7	9.5	6.0	4.4		6.3	6.7	13.5
Mollusca								
California market squid		0.9	2.4	12.0	6.3	6.3	6.7	6.0
Unidentified cephalopod		0.9	2.4					0.7
Unidentified bivalve, Veneroida		0.9						0.2
Total		2.7	4.8	12.0	6.3	6.3	6.7	6.9

for halibut from 400 to 599 mm, but northern anchovy and Pacific sardine were still an integral part of their diet (Tables 1-4). Measurements of displaced volume indicated larger fish (chub mackerel, *Scomber japonicus*; jack mackerel, *Trachurus symmetricus*; and white croaker) were incorporated into the diet of halibut $\geq$ 600 mm (Table 4). Over all size classes, we identified fishes from 12 different families in the stomach samples; Pacific sardine was highest in relative importance (Tables 1 and 5).

Table 4. Food items of California halibut ranked by percent volumetric displacement.

	Length group							
	200-299	300-399	400-499	500-599	600-699	700-799	800-1099	Total
Osteichthyes								
White croaker		1.6	6.8	11.3	14.0	58.6	57.3	23.5
Pacific sardine		38.2	22.6	11.1	6.0	9.5		16.9
Unidentified remains	43.9	28.7	24.5	31.8	21.0	5.5	19.0	15.8
Northern anchovy	14.3	15.1	10.1	11.3	7.2	9.4	15.4	11.6
Chub mackerel					36.9			9.1
Sanddab	21.7	3.9	0.3	7.6			7.7	4.7
Basketweave cusk-eel	3.3	0.1	4.0	13.7				3.6
Longspine combfish				1.9	1.7			0.9
Pink seaperch		3.5	3.0					0.9
Queenfish						7.1		0.6
California lizardfish			4.1					0.6
Rockfish			1.2		1.2			0.5
Jack mackerel					5.0			0.1
Unidentified sculpin				0.2				0.1
English sole		0.3						<0.1
Total	83.2	91.4	76.6	88.9	93.0	90.0	99.4	88.8
Crustacea								
Blackspotted bay shrimp	11.3	4.0	0.9					0.7
Unidentified remains	4.4	0.1	<0.1	0.3			0.3	0.2
Ridgeback rock shrimp			0.2	0.4				0.1
Unidentified mysid	<0.1	<0.1						<0.1
Unidentified shrimp, *Natantia*	1.0					0.2		<0.1
Mantis shrimp		0.3						<0.1
Xantus swimming crab	0.3							<0.1
Total	17.0	4.4	1.1	0.7		0.2	0.3	1.0
Mollusca								
California market squid		2.8	21.7	10.4	7.0	9.8	0.3	9.7
Unidentified cephalopod		1.4	0.6					0.3
Unidentified bivalve, Veneroida		0.1						<0.1
Total		4.3	22.3	10.4	7.0	9.8	0.3	10.0

Invertebrates were less important in the stomach contents of California halibut than fishes, although crustaceans dominated the diet of halibut < 300 mm (Tables 1, 2, and 3). Mysidacea were the most important invertebrates in these small halibut, followed by blackspotted bay shrimp, *Crangon nigromaculata*. The blackspotted bay shrimp and ridgeback rock shrimp, *Sicyonia ingentis*, replaced the Mysidacea in relative importance for halibut 300 to 599 mm (Tables 1-5). We identified five

Table 5. Summary of food items of California halibut ranked by percent Index of Relative Importance (IRI).

	Length group							
	200-299	300-399	400-499	500-599	600-699	700-799	800-1099	Total
Osteichthyes								
Pacific sardine		79	58	8	25	5		35
Northern anchovy	23	12	21	21	5	36	11	21
White croaker		<1	1	11	16	46	79	16
Sanddab	42	2	<1	3			9	5
Chub mackerel					44			2
Basketweave cusk-eel	3	<1	4	13				2
Miscellaneous fishes (> 8 spp.)		<1	2	1	2	4		<1
Total[a]	46	99	98	96	98	96	99	95
Crustacea								
Blackspotted bay shrimp	15	5	<1					3
Unidentified mysid	16	1						1
Miscellaneous Crustacea	1	<1	<1	1		2		<1
Total[b]	54	1	<1	<1		1	<1	2
Mollusca								
California market squid		<1	12	42	7	7	1	15
Unidentified cephalopod		<1	1					<1
Unidentified bivalve, Veneroida		<1						<1
Total		<1	1	4	2	3	<1	2

[a] Includes unidentified fish remains.
[b] Includes unidentified crustacean remains.

families and one suborder of crustacea in stomachs. Of the crustacea, blackspotted bay shrimp had the highest overall IRI value (Tables 1 and 5). Crustacea were essentially nonexistent in the diet of halibut ≥ 500 mm and were replaced by California market squid, *Loligo opalescens*. (Tables 1-5). Other than California market squid, mollusks were a rare component of halibut diet (Table 2). A total of three unidentified cephalopods (beaks) and one unidentified bivalve (Veneroida) completed the mollusk component.

DISCUSSION

Our data show that, as California halibut grow, the composition and relative importance of prey species change to include progressively larger prey (Tables 1-5). Halibut made a transition from feeding primarily on crustaceans to feeding primarily on fishes at 300 mm (Tables 1-5). This supports the previous findings of Haaker

1975; M.J. Allen[3] 1982, 1990; Roberts et al. 1982; Plummer et al. 1983; L.G. Allen 1988; Drawbridge[2] 1990. California market squid was a minor, but potentially seasonally important, component for a large size range of halibut (Tables 1-5).

Pacific sardines dominated the diet of California halibut from 300 to 499 mm and 600 to 699 mm (Tables 1-5), contrary to previous studies that found northern anchovies in this role (Schott 1971; M.J. Allen[3] 1982, 1990; Roberts et al. 1982; Plummer et al. 1983; Kramer and Sunada 1992). This difference may be due to temporal changes in the relative abundance of these two species. Since 1990, California landings of Pacific sardine have been on the rise (Barnes et al.[4] 1996), following 37 yr of very low population levels and a complete closure of the directed sardine fishery from 1967 to 1985 (Wolf 1992). In addition to the increased sardine biomass, California has experienced a dramatic decrease in the northern anchovy population since 1983, resulting in historically low commercial landings (Jacobson et al.[5] 1995).

The California halibut has been described by Haaker (1975) and M.J. Allen[3] (1982, 1990) as an ambush predator. Sixty-nine percent of the halibut stomachs examined in our study were empty, which is common for this type of predator.

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PREVALENCE OF ANTIBODIES AGAINST SELECTED DISEASES IN SAN JOAQUIN KIT FOXES AT CAMP ROBERTS, CALIFORNIA

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Prevalence of antibodies against selected pathogens in a San Joaquin kit fox, *Vulpes macrotis mutica*, population were investigated at Camp Roberts Army National Guard Training Site, Monterey and San Luis Obispo counties, California in 1989 and 1990. Prevalence of antibodies was determined from serum samples collected from 47 (26 female, 21 male) adult kit foxes and eight (four female, four male) juveniles. Antibodies were detected against five of the eight pathogens tested: canine distemper virus, canine parvovirus, infectious canine hepatitis virus, *Leptospira interrogans*, and *Toxoplasma gondii*. Antibodies were not detected against *Brucella canis*, *Yersinia pestis*, or *Coccidioides immitis*.

INTRODUCTION

The San Joaquin kit fox, *Vulpes macrotis mutica*, population was listed as endangered by the U.S. Fish and Wildlife Service in 1967 (U.S. Department of the Interior[2] 1967). The primary cause of the fox's endangered status is habitat loss to agricultural, industrial, and urban development (O'Farrell[3] 1983).

Prevalence of antibodies in adult San Joaquin kit foxes inhabiting the Elk Hills Naval Petroleum Reserves in Kern County and the Elkhorn Plain, San Luis Obispo County, California has been reported (McCue and O'Farrell 1988). Prevalence of antibodies in a San Joaquin kit fox population in Monterey and San Luis Obispo counties, California was investigated as part of a study of the effects of military activities on kit foxes at the Camp Roberts Army National Guard Training Site.

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STUDY AREA

Camp Roberts is a federally owned military training site operated by the California Army National Guard. It is located approximately 43 km east of the Pacific Ocean, midway between Los Angeles and San Francisco along U.S. Highway 101. Camp Roberts encompasses 172 km^2 of mostly gently rolling hills that form a transition zone between the Salinas River floodplain and the steep foothills of the Santa Lucia Mountains. Elevations range between 161 and 521 m above sea level. Average annual rainfall is 28.5 cm and over 90% occurs between November and April (Nakata and Associates[4] 1987). Fog is common in winter months. Dominant vegetation associations are grassland; oak, *Quercus* spp., woodland; mixed chaparral; and riparian habitat. Kit foxes occur mainly in the grasslands and low to medium density oak woodlands, although they also occupy developed areas of the installation where they sometimes live under buildings (Reese et al.[5] 1992).

METHODS

Blood samples were collected from kit foxes after they were captured in live traps (National Live Trap Corporation, Tomahawk, Wisconsin 54487) and handled following methods described by O'Farrell (1987). Blood samples (8-10 ml) were drawn from the foxes' jugular veins with 2.5-cm, 21-gauge needles in a 12-ml syringes. Part of each sample was transferred into a sterile Vacutainer® (Becton, Dickinson Vacutainer Systems, Rutherford, New Jersey 07070). Blood samples were refrigerated at 5°C after field collection. Each sample was centrifuged to obtain serum, which was shipped to one of the following two analytic laboratories: Veterinary Reference Laboratory, Anaheim, California and Veterinary Medicine Teaching Hospital, Department of Immunology, University of California, Davis, California. Two additional blood samples were collected from kit foxes found dead in fresh condition.

Foxes were considered to be juveniles until 30 November of their birth year because San Joaquin kit foxes can breed in their 1st yr and breeding begins in December (Zoellick et al.[6] 1987). Foxes that were not known to be juveniles (based on body size and tooth wear at time of first capture) were categorized as adults.

Serological tests were performed to determine presence of antibodies against pathogens of the following diseases that are known to occur in kit fox or other

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canids (McCue and O'Farrell 1988) or known to have severe impacts on wildlife populations (Davis et al. 1970): canine distemper virus; canine parvovirus; infectious canine hepatitis virus; brucellosis, *Brucella canis*; sylvatic plague, *Yersinia pestis*; leptospirosis, *Leptospira interrogans* serotypes *canicola*, *grippotyphosa*, *hardjo*, *icterohaemorrhagiae*, and *pomona*; toxoplasmosis, *Toxoplasma gondii*; and coccidioidomycosis, *Coccidioides immitis*. If antibodies against canine parvovirus were detected, the serum was treated with 2-mercaptoethanol (2-ME) and retested. A fourfold or greater decrease in the titer (the relative amount of antibodies in the serum) after treatment indicated the fox was exposed within 2 weeks of when the blood was drawn. The presence of antibodies against rabies virus was not determined because infected animals generally die before antibodies appear in their blood and a commercial serologic test for rabies was not available. Chi-square contingency table analysis was used to determine if significant differences in antibody occurrence existed between male and female kit foxes and between adult foxes from Camp Roberts and from other areas. Test statistics were considered significant if $P < 0.05$.

RESULTS

Presence of antibodies against selected organisms was determined in serum from 47 adult kit foxes (26 female, 21 male) and eight juveniles (four female, four male) collected between April 1989 and December 1990. Some serum samples were not large enough for all antibody tests to be performed. Antibodies were detected against five of the eight organisms tested (Table 1). There were no significant differences between male and female antibody prevalence in either age class (all P-values ≥ 0.20). There were no significant differences between the

Table 1. Prevalence of antibodies to selected diseases in San Joaquin kit foxes at Camp Roberts, 1989-1990, by age and sex. (Numbers represent the number of samples with antibodies detected over the number of samples tested.)

	Adult			Juvenile		
Pathogen	Male	Female	Both Sexes	Male	Female	Both Sexes
Canine distemper virus	3/15	5/26	8/41 (20%)	0/3	0/4	0/7(0%)
Canine parvovirus						
before 2-mercaptoethanol	11/17	20/26	31/43 (72%)	0/3	0/4	0/7 (0%)
after 2-mercaptoethanol	4/11	4/14	8/25 (32%)	-	-	-
Infectious canine hepatitis virus	5/14	5/23	10/37 (27%)	0/3	0/4	0/7 (0%)
Brucella canis	0/14	0/25	0/39 (0%)	0/3	0/4	0/7 (0%)
Yersinia pestis	0/19	0/22	0/41 (0%)	0/4	0/4	0/8 (0%)
Leptospira interrogans serotypes *canicola*, *grippotyphosa*, *hardjo*, *icterohaemorrhagiae*, and *pomona*	4/14	4/24	8/38 (21%)	0/3	1/4	1/7 (14%)
Toxoplasma gondii	4/15	3/25	7/40 (18%)	0/3	0/4	0/7 (0%)
Coccidioides immitis	0/14	0/22	0/36 (0%)	0/3	0/4	0/7 (0%)

prevalence of antibodies detected in adult foxes at Camp Roberts and the prevalence detected in samples collected from adult kit foxes at either Elk Hills Naval Petroleum Reserves or Elkhorn Plain (McCue and O'Farrell 1988) (Table 2) (all P-values ≥ 0.20).

Twenty percent of 41 adult foxes tested positive for antibodies against canine distemper virus, 72% of 43 adult fox samples tested positive for presence of antibodies against canine parvovirus (at least eight of which were recent exposures), and 27% of 37 adult fox samples tested positive for antibodies against canine hepatitis virus. Antibodies against *B. canis* and *Y. pestis* were not detected in any samples (number of samples tested = 46 and 49, respectively). Twenty-one percent of 38 samples from adult kit foxes tested positive for antibodies against one or more of the five *Leptospira* serotypes studied and 18% of 40 adult fox samples tested positive for *T. gondii* antibodies. Antibodies against *C. immitis* were not detected in any of 43 samples tested. Antibodies were detected in only one of eight samples from juvenile kit foxes; a juvenile female had a titer of 1:100 for antibodies against two of the *Leptospira* serotypes (*canicola* and *grippotyphosa*).

DISCUSSION

The occurrence of antibodies against the pathogens tested is similar to that reported for adult San Joaquin kit foxes by McCue and O'Farrell (1988), with two exceptions: *Leptospira interrogans* and *Toxoplasma gondii*. Over 21% of the 38 samples collected from adult kit foxes during this study tested positive for antibodies against one or more of the *Leptospira* serotypes, whereas detectable levels were not found in any of 23 kit fox blood samples collected by McCue and O'Farrell (1988)

Table 2. Comparison of the prevalence of antibodies to selected diseases in adult San Joaquin kit foxes at Camp Roberts, Elk Hills Naval Petroleum Reserves (McCue and O'Farrell 1988), and Elkhorn Plain (McCue and O'Farrell 1988). (Numbers represent the number of samples with antibodies detected over the number of samples tested.)

Pathogen	Camp Roberts	Elk Hills	Elkhorn Plain
Canine distemper virus	8/41 (20%)	4/42 (10%)	0/2 (0%)
Canine parvovirus			
before 2-mercaptoethanol	31/43 (72%)	21/26 (81%)	1/1 (100%)
after 2-mercaptoethanol	8/25 (32%)	6/26 (23%)	1/1 (100%)
Infectious canine hepatitis virus	10/37 (27%)	7/43 (16%)	0/2 (0%)
Brucella canis	0/39 (0%)	5/23 (22%)	0/13 (0%)
Yersinia pestis	0/41 (0%)	0/8 (0%)	0/3 (0%)
Leptospira interrogans serotypes *canicola*, *grippotyphosa*, *hardjo*, *icterohaemorrhagiae*, and *pomona*	8/38 (21%)	0/23 (0%)	-
Toxoplasma gondii	7/40 (18%)	0/25 (0%)	2/10 (20%)
Coccidioides immitis	0/36 (0%)	0/27 (0%)	1/9 (11%)

(Table 2). The lack of detectable antibodies in blood samples collected from kit foxes at Elk Hills is not easily explained. Cirone et al. (1978) found antibodies against *Leptospira* organisms in 89% of 62 wild carnivores tested in California.

Antibodies against *T. gondii* were detected in 18% of the adult samples collected from Camp Roberts, whereas McCue and O'Farrell (1988) did not detect any in 25 samples collected at Elk Hills in Kern County (Table 2). However, McCue and O'Farrell (1988) did detect antibodies against *T. gondii* in two of 10 samples collected from kit foxes on the Elkhorn Plain in San Luis Obispo County. The reason for the lack of detectable antibodies against *T. gondii* in blood samples collected from kit foxes at Elk Hills is not clear. Riemann et al. (1978) found that antibodies against *T. gondii* were present in 25% of 213 wild canids tested throughout California and 56% of 127 wild felids tested.

Eight of the 41 (20%) foxes tested had antibodies against canine distemper virus, which is slightly higher than the 4 of 44 (9%) reported by McCue and O'Farrell (1988) (Table 2).

Thirty-nine adult kit foxes from Camp Roberts tested negative for presence of antibodies against *B. canis* (Table 1). All 13 of the foxes from the Elkhorn Plain tested negative for *B. canis* antibodies, but five of the 23 (22%) from the Naval Petroleum Reserves tested positive (McCue and O'Farrell 1988) (Table 2). This pattern was not expected because brucellosis is considered a disease associated with domestic animals (Bruner and Gillespie 1973); both Camp Roberts and the Elkhorn Plain are grazed by livestock, but the Naval Petroleum Reserves are not. The source of exposure at the Naval Petroleum Reserves is not known (McCue and O'Farrell 1988). Brucellosis has been reported in canids, felids, and mustelids inhabiting livestock areas in California (Hoq 1978). The occurrence of antibodies to *B. suis* is relatively common in feral pigs in Monterey and San Luis Obispo counties (Drew et al. 1992) and they are known to cross-react in tests for antibodies to the other *Brucella* species (D. Jessup, California Department of Fish and Game, pers. comm.). However, as feral pigs are present at Camp Roberts and not the Naval Petroleum Reserves, this still does not explain the anomalous results.

Ten of the 37 (27%) adult foxes from Camp Roberts had antibodies present against the infectious canine hepatitis virus, which is similar to the 7 of 45 (16%) tested by McCue and O'Farrell (1988) (Table 2). Thirty-one of the 43 (72%) adult foxes tested positive for antibodies against canine parvovirus, which is slightly lower than the 82% (22 of 27) of the foxes tested by McCue and O'Farrell (1988) (Table 2).

The lack of antibodies against *Y. pestis* in the 41 adult and eight juvenile foxes tested at Camp Roberts (Table 1) is notable as it relates to the wild carnivore serology program at the California Department of Health Services that is using such data to determine plague activity among rodent populations in the state (Smith et al. 1984). *Yersinia pestis* is known to be widely distributed in California (including Monterey and San Luis Obispo counties) and the California ground squirrel, *Spermophilus beecheyi*, which is one of the most important prey items consumed by

kit foxes at Camp Roberts (Logan et al.[7] 1992), is considered to be one of the most important species in plague epidemiology (Nelson 1980). McCue and O'Farrell (1988) found no antibodies against *Y. pestis* in 11 foxes tested (Table 2).

None of the 36 adult foxes tested positive for the presence of antibodies against *C. immitis* (Table 1). This was unexpected because kit fox burrows appear conducive to the growth of this soil fungus (McCue and O'Farrell 1988). McCue and O'Farrell (1988) found that only one of 36 (3%) kit foxes they tested had *C. immitis* antibodies present (Table 2).

While the prevalence of antibodies to the rabies virus was not tested, the virus was known to be present in the Camp Roberts population. In early 1990, two kit foxes were found dead due to rabies (Standley et al.[8] 1992). There was one other incident of rabies in kit foxes in 1989 when a rabid desert kit fox, *V. m. arsipus*, was found in Death Valley National Monument (N. Hagerman, National Park Service, pers. comm.). Raccoons, *Procyon lotor*, and striped skunks, *Mephitis mephitis*, were regularly captured while trapping for kit foxes at Camp Roberts (EG&G Energy Measurements, Inc.[9] 1991) and both are known vectors of rabies. San Luis Obispo County had the highest incidence of wildlife rabies cases of all counties in California during this study (Barrett 1990, Schultz and Barrett 1991).

The lack of antibodies in juvenile kit foxes against seven of the eight pathogens tested for was not unexpected because of their limited opportunity for exposure. While no juvenile kit foxes tested had antibodies against infectious canine hepatitis or canine parvovirus, they are both known to have high potential to cause juvenile mortality in canids (Appel et al. 1980, Cabasso 1970).

Serological tests indicated that pathogens of at least five diseases are present on Camp Roberts: infectious canine hepatitis, canine parvovirus, leptospirosis, toxoplasmosis, and canine distemper. There was no indication of the presence of the pathogens that cause brucellosis, sylvatic plague, or coccidioidomycosis. It should be noted that while a positive titer against a pathogen suggests prior exposure, it does not necessarily indicate the presence of the disease. While infectious disease (rabies) was known to cause the death of two radio-collared kit foxes between November 1988 and September 1991 (Standley et al.[8] 1992), infectious diseases may have been the ultimate cause of deaths attributed to predation or unknown causes.

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THE OCCURRENCE OF HYDROGEN SULFIDE GAS IN SAN JOAQUIN KIT FOX DENS AND RODENT BURROWS IN AN OIL FIELD IN CALIFORNIA

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We measured levels of hydrogen sulfide gas (H_2S) in kit fox, *Vulpes macrotis mutica*, dens; rodent burrows; and ambient air at oil-developed and control sites in southwestern Kern County, California. Hydrogen sulfide levels in ambient air and fox dens at the oil-developed site were higher than those at the control site, but were lower than concentrations known to cause health effects to animals. Hydrogen sulfide levels in rodent burrows at the undeveloped site were higher than levels at 60-cm depths in kit fox dens at the oil-developed site. This suggests that exposure risks to fossorial mammals at the oil-developed site are similar to that occurring from the natural decay of plant material found in rodent caches. However, exposure effects to animals from repeated, low-level concentrations (i.e., < 1.0 ppm) of H_2S are unknown.

INTRODUCTION

Hydrogen sulfide (H_2S) is a toxic, colorless gas that occurs in ambient air at average levels between 0.0001 and 0.001 ppm (Robinson and Robbins 1970) and can be lethal to humans and experimental animals at 300-500 ppm (WHO 1981). Hydrogen sulfide is both an irritant and an asphyxiant gas. Exposure to a single high concentration (1,000 ppm) or to prolonged (about 3 h) medium concentrations (100 ppm) can cause acute respiratory and nervous system distress. There is no information on the effects of long-term, low-level exposure to H_2S gas to either humans or animals (WHO 1981). Concentrations as low as 0.025 ppm can be detected by smell. However, the gas causes olfactory paralysis as concentrations approach 150 ppm.

Point sources that produce H_2S naturally or as a by-product, such as wood pulp processing plants and geothermal areas, have nearby ambient air concentrations from 0.13 to 1.4 ppm (WHO 1981). Hydrogen sulfide associated with crude oil and natural gas deposits in the Midway-Sunset oil field in western Kern County, California is released during extraction and drilling activities. Two species of concern also occur in this oil field, the state threatened and federally endangered San Joaquin kit fox, *Vulpes macrotis mutica*, and the federal candidate short-nosed kangaroo rat, *Dipodomys nitratoides brevanasus*. Both are fossorial mammals and may be exposed to H_2S as the gas is heavier than air and tends to accumulate in low spots in the topography, such as dens and burrows. Massive exposures can result from the slow accumulation of H_2S in low-lying areas (WHO 1981). Extended exposure to

low-level concentrations could also occur.

The purpose of our study was to measure levels of H_2S gas in kit fox dens, rodent burrows, and in ambient air at the Midway-Sunset oil field and compare this with levels measured at an undeveloped site, the Lokern Natural Area, located 12.4 km away.

METHODS

Hydrogen sulfide samples were collected from kit fox dens and rodent burrows on separate days over a 6-d period in June 1994 from undeveloped and oil-developed sites. Hydrogen sulfide samples were collected using an H_2S gas meter (Model 02200-0200, Enmet Corporation, Ann Arbor, Michigan). An aspirator with 1.5 m of hose was connected to the gas meter to sample concentrations of the gas within the burrows and dens.

We sampled San Joaquin kit fox dens and rodent burrows over nearly rectangular areas that covered 13.7 km^2 in the oil-developed field and 11.3 km^2 in the undeveloped site. Locations for sampling rodent burrows were chosen by overlaying a grid over the study site and using a random numbers table to select coordinates. Kit fox dens did not lend themselves to the same selection process due to their limited numbers. Kit fox dens, initially located using radio-telemetry, were chosen with accessibility and, whenever possible, uniform distribution in mind.

At each den location meter readings were taken from ambient air, 30 cm in from the den entrance, and 60 cm in from the den entrance. At each rodent burrow, meter readings were taken at ambient air and 15 cm in from the burrow entrance. Ambient air readings were taken without the aspirator and hose. The meter was held 1.2 m above ground and the reading was recorded after it stabilized. Sub-ground readings were taken with the aspirator and hose attached. We put marks on the hose at 15 cm, 30 cm, and 60 cm for standardization and convenience. The sample of air was drawn to the meter by an in-line hand pump. Continuous squeezing of the bulb brought the sample to the meter and the reading was recorded after it stabilized.

T-tests or ANOVA were used to compare mean H_2S ppm at the different depths of measurement within and between sites for kit fox dens and rodent burrows. Ambient air readings were compared within sites among all survey days to determine whether these could be combined to compare ambient readings between sites. Comparisons of ambient air readings to readings at different burrow and den depths were done using data from the same day of collection.

RESULTS

We sampled 40 dens and 35 rodent burrows at the undeveloped site and 32 dens and 37 rodent burrows at the developed site (Table 1). Ambient air temperature during the collection period (1200-1700) was as low as 31°C at noon and as high as 36°C late in the afternoon. Intermittent gusts of wind did not exceed 9.7 km/h during sampling.

Ambient air in the developed site had higher concentrations of H_2S than ambient

air in the undeveloped site for readings taken only during den survey collection days ($t = -2.00$, 65 df, $P < 0.05$) and from readings taken only during burrow survey collection days ($t = -2.54$, 68 df, $P < 0.01$). Ambient air readings for all survey days within sites did not differ ($P > 0.05$) and were combined for comparisons between sites. Combined readings of ambient air H_2S levels were significantly higher in the oil-developed site than in the undeveloped site ($t = -3.13$, 141 df, $P < 0.01$).

Hydrogen sulfide levels in kit fox dens were higher in the oil-developed site than in the undeveloped site at both 30 cm ($t = -2.71$, 69 df, $P < 0.01$) and 60 cm ($t = -3.54$, 67 df, $P < 0.001$). In the undeveloped site, there were no significant differences in H_2S levels between ambient, 30-cm depth, and 60-cm depth ($F = 2.44$; 2, 116 df; $P = 0.09$). In the oil-developed site, H_2S levels differed between ambient, 30-cm depth, and 60-cm depth ($F = 4.75$; 2, 95 df; $P = 0.01$). Readings at 60 cm were significantly higher than ambient readings ($t = -3.01$, 61 df, $P < 0.01$). Den readings at 30-cm depths did not differ from ambient readings.

Hydrogen sulfide readings at 15-cm depths in rodent burrows were not significantly different between sites ($P > 0.05$). Within each site, however, readings 15 cm deep were significantly higher than ambient readings at both the undeveloped ($t = -3.84$, 54 df, $P < 0.001$) and oil-developed sites ($t = -5.63$, 71 df, $P < 0.0001$).

DISCUSSION

Hydrogen sulfide levels in ambient air, kit fox dens, and rodent burrows at both study sites were well below concentrations known to cause health effects to humans or experimental animals. Most H_2S studies on animals, however, have focused on the effects of exposure to lethal or near-lethal concentrations of the gas (Evans 1967, Haggard 1925, Sayers et al. 1925). Controlled exposures of animals or humans to low concentrations (< 1.0 ppm) have not been reported. The earliest toxic response of humans after several hours of exposure to 10.5 to 21.0 ppm is eye and throat irritation; however, pulmonary edema has also been reported (WHO 1981). Humans

Table 1. Mean level of H_2S concentrations (ppm) in ambient air, kit fox dens, and rodent burrows in undeveloped and oil-developed areas in Kern County, California. Like superscripts denote a significant difference ($P < 0.05$).

	Undeveloped		Developed	
	n	Mean (SE)	n	Mean (SE)
Ambient air	75	0.23 (0.02)[a]	69	0.31 (0.02)[a]
Kit fox dens	40		32	
ambient		0.25 (0.02)[b]		0.33 (0.03)[b,c]
30 cm depth		0.30 (0.02)[d]		0.39 (0.02)[d]
60 cm depth		0.32 (0.02)[e]		0.43 (0.02)[c,e]
Rodent Burrows	35		37	
ambient		0.20 (0.03)[f,g]		0.30 (0.03)[f,h]
15 cm depth		0.43 (0.05)[g]		0.52 (0.03)[h]

in Terre Haute, Indiana exposed to a 1-h mean concentration of 0.3 ppm experienced nausea; sleeplessness; burning eyes; shortness of breath; and, less commonly, cough, headache, and anorexia (US Public Health Service 1964). When inhaled by dogs (concentration unknown), H_2S caused inflammation of the entire respiratory tract, with most damage experienced by the deeper structures, which could lead to pulmonary edema (WHO 1981). Rabbits exposed to 70 ppm for 1.5 h/d for 5 consecutive d experienced electrocardiographic changes (Kosimider et al. 1967). Mice exposed four times for 2 h at 4-d intervals to 100 ppm experienced a decrease in cerebral RNA synthesis and cumulative inhibition of cytochrome-c oxidase. The latter may interfere with tissue metabolic demands (Smith and Gosselin 1979). Effects of long-term, low-level exposure are unknown.

Our study has established that H_2S levels were significantly higher in ambient air and in fox dens and, although not significantly higher, were 20% greater in rodent burrows in the Midway Sunset oil field than in an area without oil-exploration-related activities. Conversely, H_2S levels in rodent burrows at the undeveloped site were equal to or greater than levels found in kit fox dens at either site. The occurrence of H_2S in excess of the ambient levels in the rodent burrows may be due to natural processes. Bacteria release H_2S during the decay of plant and animal materials which contain sulfur. Since small rodents usually have a cache of plant seeds in the burrow, H_2S may be produced. Hydrogen sulfide residue from decay may not be as prevalent in kit fox dens as it is in rodent burrows due to better ventilation inherent in the larger diameter tunnels. Also, kit foxes do not store seeds in dens and tend to remove prey remains prior to advanced stages of decomposition. Thus, levels of H_2S occurring in the kit fox dens in the oil field appear to pose no greater risk than levels occurring by natural processes in rodent burrows in an undeveloped setting.

The level of exposure to H_2S could be much higher than what we report during periods of fog (Minster 1963) or when prolonged hot temperatures without the presence of wind reduce ventilation to underground dens and burrows. Both of these weather conditions are characteristic of the southern San Joaquin Valley. Also, concentrations of H_2S may be higher in dens in the oil field at depths greater than 60 cm or, as H_2S is heavier than air, in dens located in low-lying areas. Indeed, our data showed that H_2S levels in dens increased with depth.

The World Health Organization's Task Group on Environmental Health Criteria for Hydrogen Sulfide recommends studies be conducted on the effects, particularly the cumulative neural effects, of continuous exposure to low concentrations (< 1.0 ppm) of H_2S. Until this type of information is available, we are unable to ascertain the exposure-effect relationships to the listed and candidate species from the data collected from this study.

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INTRODUCTION OF THE RIDGETAIL PRAWN, *EXOPALAEMON CARINICAUDA*, INTO SAN FRANCISCO BAY, CALIFORNIA

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The ridgetail prawn, *Exopalaemon carinicauda* (Holthuis 1950), is native to China and Korea where it lives in bays and brackish water. Because it is edible and fairly large (to 97 mm total length), it is commercially fished in northern China and Korea (Holthuis 1980).

I received a specimen of this species in 1993 from D. Chivers, California Academy of Sciences. The shrimp was collected by anglers off Dumbarton Point in South San Francisco Bay on 17 February 1993. L.B. Holthuis (Rijksmuseum van Natuurlijke Historie, Leiden, the Netherlands) confirmed the identification of the shrimp as *E. carinicauda*. It has been deposited at the California Academy of Sciences (CAS 104258).

K. Hieb of the California Department of Fish and Game (CDFG) later sent another specimen to me. This one was taken on 15 March 1995 in an otter trawl fished in a channel 1.4 km south of the Dumbarton Bridge in South San Francisco Bay, at a salinity of 20.6 ppt. It has been retained for the reference collection of the Bay-Delta and Special Water Projects Division of CDFG.

Exopalaemon carinicauda can be distinguished from other shrimp in San Francisco Bay by its long, toothed rostrum; the large chelae on the second pereopods; and the dorsal ridges (carinae) on the abdominal somites (Fig. 1). (The carinae are best seen in dorsal view.) As in other species of the family Palaemonidae, the first and second pereopods both bear chelae, but the first pereopods are smaller than the second. The carpus of the second pereopod is not subdivided, as is the case in native species belonging to the families Pandalidae and Hippolytidae.

The ridgetail prawn is the second member of its family to be introduced into San Francisco Bay from the coast of Asia. *Palaemon macrodactylus*, a smaller shrimp, is common throughout the bay and apparently was introduced into the area in 1954 (Newman 1963). It has a shorter rostrum than *E. carinicauda* and does not have carinae on its abdominal segments.

Exopalaemon carinicauda was probably imported for sale as bait or human food. The two collection sites are near Palo Alto, where there is a shoreline park and nature reserve. The shrimp may have been dumped with discarded bait off a boat or released from shore.

The impact of the introduction of this shrimp into San Francisco Bay is unclear. Sitts and Knight (1979) suggested that *Palaemon macrodactylus* and the native shrimp *Crangon franciscorum* might compete for food during fall. If *Exopalaemon*

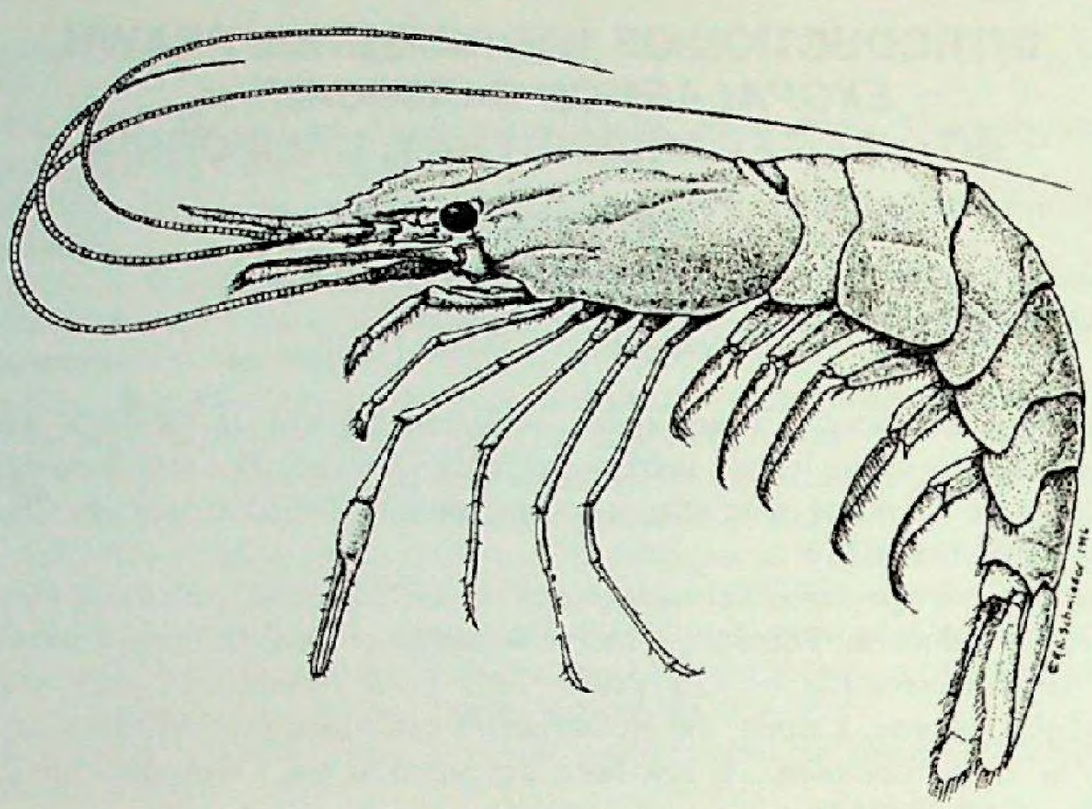

Figure 1. *Exopalaemon carinicauda* from the channel south of Dumbarton Bridge. Carapace length 20 mm.

carinicauda becomes abundant, it might offer further competition for food resources or provide another prey species for birds, fishes, or seals.

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R. Schmieder drew Figure 1.

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